Whole-body vibration of heavy mobile equipment operators at an opencast mine

by

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Declaration

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Abstract

Whole-body vibration of heavy mobile equipment operators at an opencast mine

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Thesis: MEng (Mech)

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The measurement and analysis of whole-body vibration was done in accordance with ISO 2631-1 at a South African opencast mine to identify potentially unhealthy levels of vibration present in vehicles. Impulsive whole-body vibration was found on all measured vehicles and 90.6% of test cases showed possibly unhealthy levels of vibration exposure. The impulsiveness of the vibration led to the underestimation of the exposure by the RMS method. Bulldozer operators were exposed to the highest average levels of whole-body vibration. It is strongly advised that the use of high exposure vehicles are limited and that job rotation is implemented to limit the vibration exposure of these individuals. The vehicle tasks are used for as well as operating conditions were found to have a significant impact on whole-body vibration.

A suitable measurement duration for different types of vehicles were statistically identified and it was found that measurement durations greater than 30 min and 60 min are sufficient to measure whole-body vibration with measurement errors of less than 25% (sufficient accuracy) and 12.5% (preferable accuracy) respectively.

Uittreksel

Heel-liggaam vibrasie van swaar mobiele toerusting operateurs by 'n oopgroefmyn

E. Purcell

Tesis: MIng (Meg)

Desember 2017

Die meet en analise van heel-liggaam vibrasie is in ooreenstemming met ISO 2631-1 by 'n Suid-Afrikaanse oopgroefmyn gedoen om moontlike ongesonde vlakke van vibrasie teenwoordig in voertuie te identifiseer. Impulsiewe heel-liggaam vibrasie was in alle voertuie teenwoordig en 90.6% van toetsgevalle het gedui op moontlike ongesonde vlakke van vibrasie blootstelling. Die impulsiwiteit van die vibrasie het gelei tot die onderskatting van die blootstelling vlakke deur die RMS-metode. Stootskraperoperateurs was aan die hoogste gemiddelde vlakke van heel-liggaam vibrasie blootgestel. Dit word sterk aanbeveel dat die gebruik van hoë blootstelling voertuie beperk word en dat werksrotasie geïmplementeer word om die vibrasie blootstelling van dié individue te beperk. Dit is bevind dat die taak waarvoor die voertuie gebruik word, sowel as die operasionele omstandighede, 'n noemenswaardige invloed op heel-liggaam vibrasie het.

'n Geskikte meettydperk vir verskillende tipes voertuie is statisties geïdentifiseer en dit is bevind dat meettydperke langer as 30 min en 60 min voldoende is om heel-liggaam vibrasie te meet met meetfoute kleiner as 25% (voldoende akkuraatheid) en 12.5% (gewenste akkuraatheid) onderskeidelik.

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Dedications

Dinalize, thank you for always making me laugh. I could not have done this without you.

Thank you to Hendrik, Angelique and Nicole for providing welcome distractions from my studies, be it with Ark, Catan, Canasda, SH or Risk.

Finally I want to thank my parents for their continued support.

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Nomenclature

CF crest factor

CV coefficient of variation

EAV exposure action value

ELV exposure limit value

EU European Union

HMC heavy mineral concentrate

HME heavy mobile equipment

HVM human vibration meter

IIR infinite impulse response

MEMS micro-electro-mechanical

MTVV maximum transient vibration value

RBM Richards Bay Minerals

RMS root-mean-square

VDV vibration dose value

VTV vibration total value

WBVHSQ whole-body vibration health surveillance questionnaire

WBV whole-body vibration

Variables

A	peak acceleration	[m/s^2]
a	acceleration	[m/s^2]
b	age at which work was started	[a]
f	frequency	[Hz]
D	impulsive vibration dose	[m/s^2]
d	displacement	[m]
G	filter gain	[ ]
H	filter function	[ ]
k	axis factor	[ ]
N	working days per year	[d]
n	current age of individual	[a]
P	major neural network constant	[ ]
p	minor neural network constant	[ ]
Q	filter constants	[ ]
R	impulsive vibration exposure factor	[ ]
S	stress	[MPa]
s	Laplace space variable	[rad/s]
T	duration	[s]
t	time	[s]
VDV	vibration dose value	[$m/s^{1.75}$]
v	velocity	[m/s]
W	weighting function	[ ]
w	weighting value	[ ]
σ	standard deviation	[ ]
τ	integration time	[s]
ω	frequency	[rad/s]

Subscripts

0	reference value
8	eight hour equivalent
b	weighting function identifier
c	weighting function identifier
d	weighting function identifier
E	equivalent
e	estimated
H	high pass
i	increment $i = 1,2,\ldots$
j	increment $j = 1,2,\ldots$
k	weighting function identifier
L	low pass
l	lumbar spine
n	normalised
p	axis $p = x,y,z$
S	upward step
s	seat pad
T	acceleration-velocity transition
u	ultimate
v	total vibration
w	weighted
x	x-axis
y	y-axis
z	z-axis

Chapter 1

Introduction

The mining sector exposes workers to a wide array of occupational risks. These risks manifest in safety problems such as the dropping of heavy objects, falling from heights, drowning, burning, entanglement in machinery and entrapment in confined spaces (Mining Review Africa, 2015; Hermanus, 2007). These risks are mostly managed by safety gear, warning systems and training. The effects of these events can be severe and in some cases deadly. Due to the easily understood nature of these risks and the severity and visibility of the consequences, mineworkers are aware of them and actively avoid these risks (Mining Review Africa, 2015).

The mining environment potentially exposes workers to more subtle dangers, such as health risks. These are factors that increase the chance of adverse health effects (World Health Organisation, 2009). These risks arise due to exposure to foreign chemical substances, such as charcoal dust, toxic gases and carcinogenic material, as well as physical agents (Hermanus, 2007; Republic of South Africa, 1993). The effects that arise from these hazards are especially unhealthy as the health effects develop gradually and are thus not immediately noticeable and in some cases only detectable by medical testing. To limit these risks, mines implement training, monitoring of hazards, safety gear and scheduling of tasks. The physical agents that most commonly cause health risks at mines are noise, radiation, UV exposure and vibration (Mining Review Africa, 2015; Republic of South Africa, 1993).

Vibration is known to cause damage to the musculoskeletal, respiratory, reproductive, sensory and ciculatory systems (Mining Review Africa, 2015; International Organization for Standardization, 1997; South African Bureau of Standards, 1997; Aye and Heyns, 2011; Griffin, 1990). The main forms of vibration relevant to occupational health are hand-arm vibration and whole-body vibration (International Organization for Standardization, 1997, 2001). Whole-body vibration (WBV) is the vibration exerted on a person by a surface supporting the body. WBV is a great concern in the mining sector as it is present in vehicles, machinery and industrial activities and can interfere with the health of the exposed individual (Mining Review Africa, 2015). These injuries mostly associated with WBV are found in the spine, abdomen and cardiovascular system (Paschold, 2008). The symptom mostly associated with WBV exposure of seated operators is morbidity of the lower spine (Griffin, 1990). Comité Européen de Normalisation (1996) estimated that 4% to 7% of employees are exposed to unhealthy levels of WBV in some countries.

The physical attributes of the human body can influence the vibration and in some cases amplify the vibrational energy (Paschold, 2008). Factors that influence WBV are the posture of the person, the material of the supporting surface, the frequency of vibration and the axis in which the motion occurs (Griffin, 1990). In order to enable the comparison of WBV measurements from different environments, the measurement and assessment of WBV is standardised in ISO 2631-1 (International Organization for Standardization, 1997).

ISO 2631-1 provides a standard for measuring WBV and key methods in which to analyse this data. As WBV is frequency dependent, the standard advises the use of weighting curves which attenuate the amplitude of vibration at frequencies to which the human body is not sensitive and amplifies vibration at frequencies of importance. The typical frequency range for WBV is from 0.5 Hz to 80 Hz. After the weighting, ISO 2631-1 recommends metrics by which to calculate the severity of the WBV and when to implement these calculations. This standard does not identify which activities are likely to cause high levels of WBV or what levels of vibration are considered to be unhealthy. Due to this, no legally enforceable limits are present in this standard. Research has however shown that problematic WBV exposure is a factor that potentially affects the operators of heavy mobile equipment (HME).

The need to measure, quantify and negate the effects of WBV in HME was, amongst others, identified by Aye and Heyns (2011). This research showed that accepted WBV norms, according to Directive 2002/44/EC (European Parliament, 2002), are exceeded on half of the measured HME activities in a South African open cast mine. They also noted the prevalence of shocks in most data and concluded that shock vibration is an important factor in analysing WBV in mining applications. The analysis of WBV with shocks are described partially by ISO 2631-1, but a more comprehensive analysis is done by ISO 2631-5 (International Organization for Standardization, 2004) which underlines a method for determining the probability of lumbar spinal injuries, using fatigue criteria. The work done by Zhao and Schindler (2014) identified that the operating conditions of HME have an influence on the measured vibration and that ISO 2631-5 is more conservative than ISO 2631-1 in determining whether WBV contributes to an unsafe working environment.

As WBV is a health and safety risk in high-vibration environments where the person is exposed for most of their working day (Smith and Leggat, 2005), it is of great concern to correlate the characteristics of the vibration and the prevalence of certain injuries (Griffin, 1990). Even though ISO 2631-1 establishes a standard for conducting WBV measurements and analysis, it cannot provide suitable measurement durations for all WBV applications. It states that all data should be captured where the "duration of measurement shall be sufficient to ensure reasonable statistical precision" and that the measured vibration duration should be sufficiently long to capture a typical WBV exposure. The only clear minimum duration is stated as 227 seconds if frequencies above 0.5 Hz are to be measured and analysed accurately with one-third octave analysis. This duration is also stated to be only applicable to stationary random vibration profiles. Due to the lack of clear guidance, some work has been done to clarify what a suitable duration is.

Mansfield *et al.* (2003) concluded that representative WBV measurements should be longer than 10 minutes. This was done by comparing the decrease of variance in the results of WBV metrics (according to ISO 2631-1) with the increase in measurement duration. The results show that as measurement duration increases, the data more accurately describes the WBV exposure for an eight hour working day. The conclusion of this research was that all measurements should be at least 10 minutes long, but that a preferable duration is longer than 30 minutes. The assumptions of this work includes that all data is distributed normally and the results assume that the WBV is not impulsive. The need to further study the impact of duration on accuracy is also identified by Mansfield *et al.* (2003).

The aim of the current work was to measure and quantify WBV of seated HME operators at Richards Bay Minerals (RBM). This includes the measurement of WBV on the fleet of vehicles at RBM and the identification of problematic tasks and vehicles (Figure 1.1). The data was further used to evaluate appropriate measurement durations in the present mining environment. This was done by measuring the WBV in the vehicles for extended periods of time and then assuming that only subsets of that period was captured as part of a routine WBV monitoring strategy. To further explore the efficient implementation of ISO 2631-1 by expanding the work done by Mansfield *et al.* (2003), this analysis was done with no assumptions on normality and was conducted on impulsive vibration. This project was initiated to determine practically applicable measurement approaches that deliver reliable results.

The measurement and analysis of WBV was performed according to ISO 2631-1 for 32 distinct cases on 22 different vehicles. The vehicles consisted of ten bulldozers, three excavators, two forklifts, six loaders and one off-road passenger vehicle (4x4). The exposure of dozer operators received intentional focus as they are more probable to cause excessive levels of WBV (Aye and Heyns, 2011). The data was captured alongside descriptive data such as the road surface and seat condition to allow for further comparison and contextualisation. The data was then compared to Directive 2002/44/EC which provides legally enforceable limits to determine the allowable WBV exposure in an occupational environment for EU compliant companies. The appropriate measurement duration was determined by aiming to measure the full shift completed by the vehicle operators. This allowed for the WBV exposure of an actual shift of operating HME to be directly measured. This data was statistically evaluated to determine the impact of increasing measurement duration.

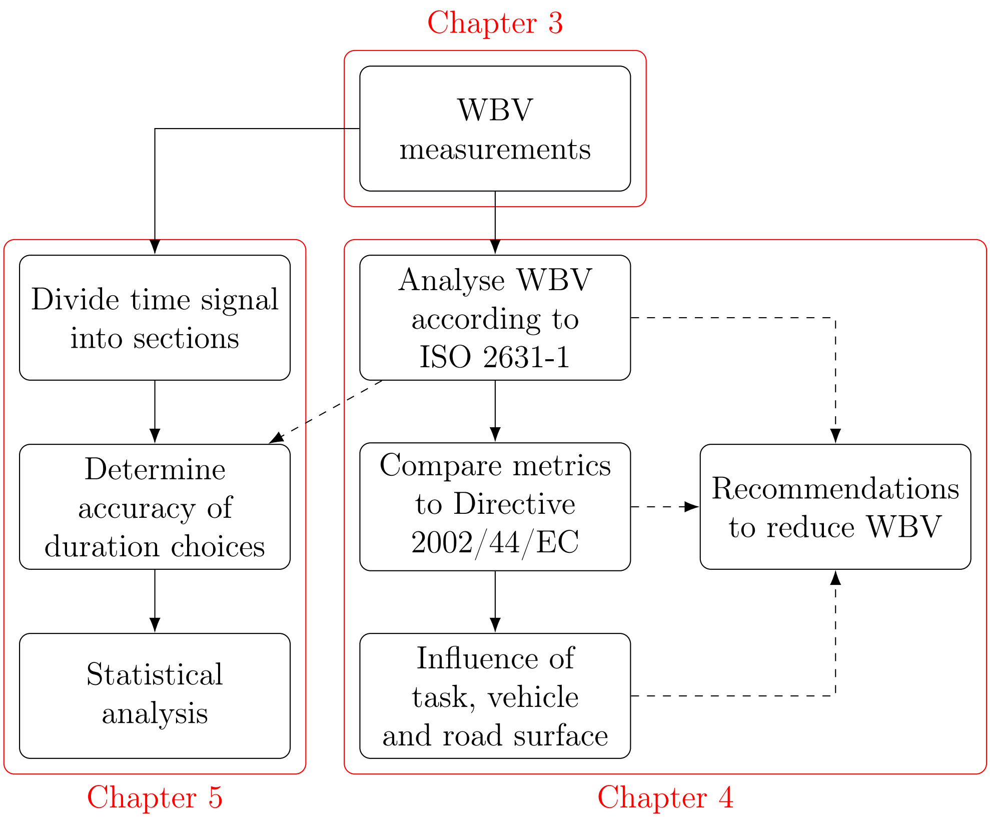


Figure 1.1: Flow chart of project

Chapter 2

Literature study

Whole-body vibration (WBV) is the vibration experienced by a human due to the body being supported by a vibrating surface. The three postures in which people experience WBV are standing, lying down or seated (Griffin, 1990). The most commonly encountered posture in commercial applications involves WBV for a seated individual. Here, vibration is transmitted to the body through the upper thighs and ischial tuberosities (Paschold and Mayton, 2011; International Organization for Standardization, 1997). The focus of this chapter is to summarise the theoretical basis and necessity for the measurement and analysis of WBV according to international standards and academic practices. The method stipulated by ISO 2631-1 for the measurement of WBV is discussed. The frequency range of importance is accounted for by the use of weighting filters and this weighted data is then analysed to obtain metrics which allow WBV measurements from different environments to be compared. Methods for the selection of suitable metrics are given by ISO 2631-1, but the occupational limits to which these metrics have to adhere (for EU compliant companies) are contained in Directive 2002/44/EC (European Parliament, 2002).

2.1 Health impacts

The cause-effect relationship between WBV and impaired health is greatly dependent on the individual's susceptibility, or predisposition, to the health effect (Griffin, 1990). Health effects can be divided into two categories: acute and chronic. Acute injuries are associated with instantaneous symptoms and therefore arise from a single event. Chronic conditions are injuries that arise over time due to continued exposure to an agent (WBV in this case). Griffin (1990) also notes that the effects arising from exposure to WBV can be either physiological or pathological. Figure 2.1 depicts the categorisation of health effects.

Figure 2.1: Categorisation of health impacts

2.1.1 Physiological effects

Physiological effects refer to changes to the normal function or rhythm of the body and they are mostly associated with acute conditions (Griffin, 1990). An example of a physiological effect is the change of heart rate. The physiological effects of WBV can be presented under various headings that aim to group numerous effects. These groupings are not mutually exclusive and in some cases they do not capture all relevant effects.

WBV with a high magnitude in the frequency range of 2 to 20 Hz can cause an increased heart rate similar to moderate exercise. This is attributed to voluntary and involuntary contraction of muscles as the individual tries to mitigate the effect of the vibration (Paschold and Mayton, 2011). This phenomenon is used in some cases as a method of exercise with the use of a WBV platform. Exercise programs consisting of WBV have been found to improve knee strength, posture stability and general health in elderly persons. Wirth *et al.* (2011) found that trunk muscle activity increases in healthy adults when exposed to WBV and Rehn *et al.* (2006) showed that prolonged WBV training can lead to improved leg muscle performance. Another cardiovascular response is that WBV reduces the ability of the body to cool itself during exposure by reducing blood flow and perspiration rate (Griffin, 1990).

The initial response of the respiratory system when exposed to WBV is hyperventilation, which slowly subsides with prolonged exposure (Duffner *et al.*, 1962). Some cases have reported observations of increased oxygen consumption with an increase in vibration magnitude. This increase in consumption is attributed to pain caused by the WBV or increased muscle activity (Griffin, 1990). Hansen *et al.* (2012) found no significant correlation between WBV exposure of helicopter pilots at high altitudes and oxygen levels in the blood. This study was performed in operational conditions and the lack of influence on the respiratory system was presumably due to low vibration intensity.

Vibration can influence the motor processes in the muscles and tendons (Arora and Grenier, 2013). De Gail *et al.* (1962) found that the efficiency of certain reflexes, such as the efficiency of the Achilles tendon reflex, can be reduced while a person is exposed to WBV. This is due to sensitivity of the muscle spindle endings. Low frequency WBV causes electrical activity in the muscles that interferes with the normal function of the spindle endings. The vibration of muscles in the arms and legs can also cause confusion as to where the limb is positioned at high frequencies. WBV can additionally reduce the postural control of the person as it introduces noise into the signal that gives the brain feedback on postural equilibrium (Griffin, 1990). Arora and Grenier (2013) found that WBV exposure causes a decrease in the ability of the nervous system. This decrease is temporary and the nerves return to their original capabilities after a short rest period.

The extended exposure of a person to WBV can lead to balance disorders as the inner ear adapts to the experience of regular movement. When this movement ceases, the body overcompensates and the person experiences an illusion of motion (Griffin, 1990). Mani *et al.* (2010) states that some evidence points to a direct correlation between seated WBV exposure and standing balance.

The vision of an exposed individual can be affected by WBV as resonance of the eye can cause blurry vision. Hearing can also be damaged by prolonged WBV exposure (Griffin, 1990). These effects are frequency dependent and explored in Section 2.4.3.

The skeletal system can be damaged as WBV causes degeneration of the bone density and cartilage (Griffin, 1990). This is a chronic effect that arises from long-term WBV exposure. The main health risk associated with the skeletal system is injuries of the lumbar spine (ISO 2631-5). These lower back injuries are most prominently reported among individuals exposed to long-term WBV (Wikström *et al.*, 1994). Acute conditions of the skeletal system are also possible as single high amplitude events can cause bone fractures (Griffin, 1990).

2.1.2 Pathological effects

Pathological effects encompass all states where the normal functioning of the body is disturbed or prevented. Medically such effects relate to an organic or structural effect which causes functional changes in the body. Due to ethical considerations, very little research exists that test the correlation between WBV and pathological effects (Griffin, 1990).

Various experiments on animals concluded that exposure to WBV can prove to be fatal in rats and monkeys (Roman, 1958; Sturges *et al.*, 1974). The main causes of death were reported to be internal haemorrhaging of the digestive system and lung damage. Pape *et al.* (1963) found that for anaesthetised cats immersed in water, a reduction of vibration magnitude proved more efficient in preventing injuries compared to reducing the duration of exposure. Increased altitude and environmental temperature decreased the required exposure time to induce death (Griffin, 1990).

Humans exposed to short duration, high magnitude WBV at frequencies between 5 and 15 Hz reported chest pain and abdominal tenderness that lasted for two days. WBV at higher frequencies had less of and impact even when the amplitude was increased tenfold (Roman, 1958). This can be due to the decrease in vibrational displacement. These results are however not representative of long-term occupational WBV due to the duration of exposure.

2.1.3 Occupational health problems

Occupational health problems arise from prolonged exposure of an individual to WBV in a work environment. Some difficulty exists in defining direct cause-effect relationships as numerous other factors can influence the results (Griffin, 1990). It is therefore hard to accurately determine the impacts that the magnitude, frequency and duration of vibration have on health problems.

Disorders which are frequently found in individuals exposed to vibration include back problems, disorders of the digestive system, disorders of the reproductive system and problems with the nervous system in descending order of prevalence (Griffin, 1990). Directive 2002/44/EC was created to, amongst other reasons, protect workers from muscular, skeletal, neurological and vascular injuries.

The prolonged exposure of a person to WBV is reported to cause severe injuries of the lower back such as displaced intervertebral discs, vertebra degeneration and osteoarthritis (International Organization for Standardization, 1997; National Institute for Occupational Safety and Health, 1997; Mansfield, 2005). In some cases WBV can also cause fatigue fractures in the vertebrae (Griffin, 1990). It is important to note that an individual working in an environment where WBV is present is in general more likely to do other activities, such as picking up heavy objects, which can increase the prevalence of back injuries (Mining Review Africa, 2015; Griffin, 1990). Decreased balance and proprioreceptor function due to WBV can increase the possibility of injuries from tasks unrelated to the vibration such as jumping or bending (Mani *et al.*, 2010).

2.2 Mitigation and prevention of health impacts

Paschold and Mayton (2011) note that vibration monitoring is paramount in WBV mitigation and prevention programs. Directive 2002/44/EC mandates WBV monitoring within the confines of the EU.

The most efficient way to reduce exposure to WBV is by reduction or elimination at the source (Griffin, 1990; Pape *et al.*, 1963). This is usually done by adjusting the equipment or by addressing environmental conditions such as road surface quality, which can prove to be extremely costly or impractical.

As an example, the seated operators of heavy mobile equipment (HME) can be isolated from vibration by means of improved designs such as correctly adjusted vehicle suspension or a suspension seat. In some cases the health impact of the WBV can be reduced without altering the vibration itself. This is achieved through ergonomic changes, such as posture, or by limiting the time of WBV exposure (Griffin, 1990). Paschold (2008) advises that the adjustment of operational conditions, such as vehicle speed, routes, maintenance schedules and job rotation can greatly decrease the prevalence of injuries.

Administrative strategies to limit exposure to WBV include the training and warning of operators as to the effect of WBV. This is beneficial from an ethical standpoint and it can cause operators to be wary of situations that can injure them. These measures can be implemented as part of mandatory training sessions (Paschold, 2008).

As good practice, regular medical surveillance and vibration monitoring can be implemented to track the influence of prolonged exposure on individuals. This aids in the early detection and prevention of reduced health and injuries in occupational environments (Griffin, 1990; European Parliament, 2002).

2.3 Vibration

Vibration is oscillatory motion with respect to a fixed position (Griffin, 1990; Mansfield, 2005). The fixed position can also be called the reference. Simple vibration waves can be described by an amplitude and frequency as shown in Equation 2.1. $a(t)$ is the time dependent acceleration, A the maximum acceleration, f the frequency in Hz and t the time in seconds. The impact of these variables on the vibration profile is shown in Figure 2.2 where the frequency is the inverse of the period required to complete a single oscillation (Inman, 2014). In general, operational vibration is more complex and has to be further classified.

$$a(t) = A \sin(2\pi f t) \tag{2.1}$$

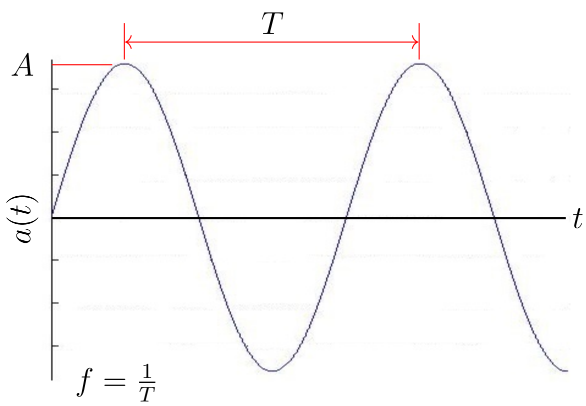


Figure 2.2: Simple sinusoidal vibration

The transient nature of vibration can vary such that it is grouped into four categories namely stationary random, non-stationary random, shock and harmonic vibration (Figure 2.3). Harmonic vibration can be described by a mathematical function (usually sinusoidal) and is periodic and completely predictable (Inman, 2014; Griffin, 1990). Vibration described by the summation of multiple sinusoidal functions is also harmonic in nature. Very few practical examples exist of pure harmonic vibration.

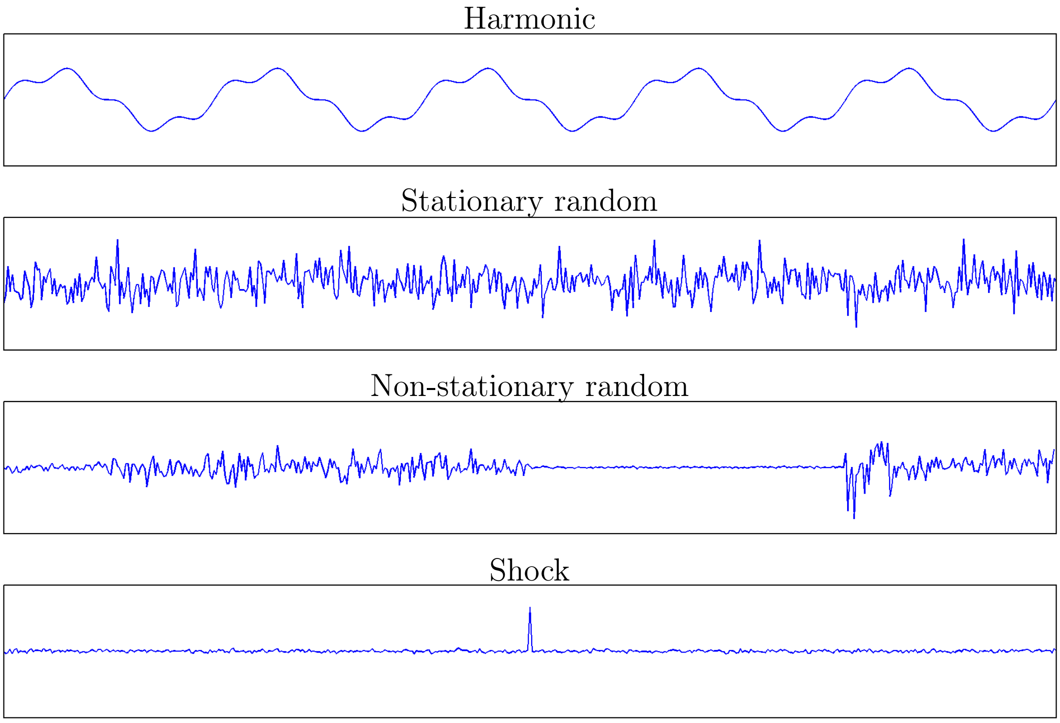


Figure 2.3: Different types of vibration

Random vibration is unpredictable and cannot simply be expressed mathematically. These signals can only be described in terms of its statistical properties such as root-mean-square (RMS) and frequency content. An example of a random signal is white noise. Random signals are subdivided into stationary and non-stationary random vibration. The RMS of a stationary random vibration signal is constant if it is calculated for a suitable duration regardless of the period during which the measurement is taken.

Non-stationary random signals are unpredictable as the magnitude and frequency content of the vibration may vary with time. The average and other metrics are thus dependent on when and how long the vibration was measured. Shock vibration is a high amplitude, single event.

WBV exerted on operators of HME is predominantly a combination of non-stationary and shock vibration (Griffin, 1990). This is attributed to changes in the tasks conducted by the operators and the unpredictability of operating circumstances. During the monitoring of occupational vibration, the duration of WBV measurements are of importance to ensure that sufficient representative data is captured.

Vibration amplitude can be described and measured as either displacement, velocity or acceleration. Acceleration is predominantly used as accelerometers are generally more accurate (Inman, 2014) and acceleration correlates with human responses to vibration. Accelerometers provide superior measurement accuracy due to the inherent relation between displacement, velocity and acceleration and acceleration magnitude does not diminish at high frequencies. Acceleration is predominantly used when analysing WBV and exclusively used when analysing the impact of WBV on health. ISO 2631-1 specifies that acceleration is to be used when analysing WBV for health impacts.

The acceleration magnitude can be quantified in terms of peak, peak-to-peak or average measures. The most notable average measure is the RMS (Griffin, 1990).

2.4 Measurement of WBV

Standards are used to gather accurate and comparable WBV data. The most widely used standards are ISO 2631-1 and BS 6841 (British Standards Institution, 1987). The proper measurement methodology and analysis methods are described in both these standards with some differences in assumptions and implementation. Directive 2002/44/EC requires measurements and analyses to be conducted according to ISO 2631-1 and this led to the wider adoption of this standard. ISO 2631-1 has also been adopted as the standard used for WBV measurement and analysis in Great Britain (ISO 2631-1).

The main purpose of this standard is to quantify WBV. The standard stipulates WBV analyses pertaining to human health, comfort, perception and motion sickness. The current project is focused on health and only information related to this is reported.

2.4.1 Measurement locations and orientation

ISO 2631-1 states that the coordinate system in which measurement is required, is basicentric with the body and that the origin of the coordinate system is at the interface between the source of vibration and the body. It is acceptable to assume that the vertical direction (the direction of gravity) is the same as the z-axis for a seated individual if the angle between these two directions is less than 15° (ISO 2631-1). It is required to record the orientation of these axes to one another.

All measurements have to be conducted at the point at which this vibration energy enters the body (ISO 2631-1). For seated persons, vibration energy transfer takes place predominantly through the buttocks and thus the required origin of the coordinate system is directly below the ischial tuberosities at the seat interface. The origin and directions of the basicentric axes are shown in Figure 2.4. Performing additional measurements at the other interfaces where vibration enters the body, namely the seat back and the floor beneath the operator's feet, is also possible. However, no clear correlation exists between vibration levels at these two points and negative WBV impacts (ISO 2631-1).

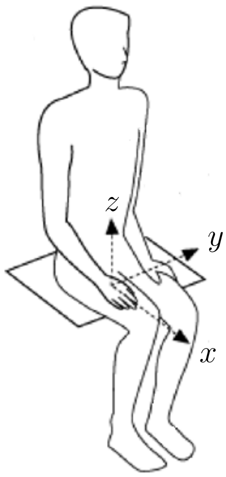


Figure 2.4: Basicentric axes of the human body in a seated position. Adapted from No More Solid Shock (S.a.)

2.4.2 Measurement duration

The measurement duration should be long enough to capture data that is representative of all experienced WBV (ISO 2631-1). The vibration profiles which are generally experienced in vehicles include a combination of non-stationary random and shock vibration (Griffin, 1990; Aye and Heyns, 2011). WBV measurements have to be long enough to negate the changes in WBV metrics due to the unpredictable nature of the vibration. This means that measurements should be accurate regardless where in the period of operation the measurement was performed. Mansfield *et al.* (2003) concluded that measurements shorter than 10 min give inaccurate results and that 30 min is long enough for accurate results. These results are based on the WBV analysis of a range of vehicles and the data was deemed accurate if the coefficient of variation (CV) of the RMS was less than 12.5%. McCallig *et al.* (2010) reported that the duration of a working shift should be accurately reported as inaccurate assumptions of shift durations can lead to errors of up to 80%.

To accurately capture low frequency vibration, at 0.5 Hz, ISO 2631-1 states that the measurement duration should be longer than 227 seconds if a one-third octave band analysis method is used for the weighting of human vibration. BS 6841 specifies that 60 seconds is the shortest allowable measurement duration and is only applicable for non-impulsive WBV. Other than these sources, only a few studies have been done that advise a suitable measurement duration.

2.4.3 Biodynamic considerations

WBV is analysed in the frequency range of 0.5 Hz to 80 Hz due to biodynamic considerations (ISO 2631-1). This range is significant as the majority of body parts and organs have a natural frequency that falls within this range (Paschold and Mayton, 2011). In the seated position, the lowest natural frequency is that of the whole body moving out of phase with the vibrating surface at 4 to 6 Hz and the highest reported natural frequency is that of the eyes at 20 to 90 Hz (Paschold, 2008).

The body is more susceptible to vibration exposure at frequencies which approximately match these various natural frequencies (Paschold, 2008). The analysis of WBV requires that the impact of this susceptibility is incorporated through the use of weighting functions (ISO 2631-1).

2.4.4 Weighting functions

To accommodate the impact that frequency has on the influence of WBV, ISO 2631-1 specifies the use of filters. These filters are used to transform acceleration signals to better account for human sensitivity to vibration of varying frequencies. The filters accentuate vibration at frequencies of high sensitivity by amplifying their contribution. Likewise, the contribution of vibration at frequencies of less significance is attenuated. The filters are described by ISO 2631-1 as a combination of four filters which are sequentially applied.

The four filters consist of a high pass-, a low pass-, an acceleration-velocity transition- and an upward step filter. These are described in Equations 2.2 to 2.5 respectively. Here ω and Q are constants that depend on the data that is being filtered. Impairment of health in people exposed to WBV at high frequencies showed a greater dependence on the velocity of the vibration rather than the acceleration. To accommodate for this dependence, the acceleration-velocity transition and upward step filters are used (ISO 2631-1).

$$\left|H_H(s)\right| = \left|\frac{1}{1 + \frac{\sqrt{2}\omega_1}{s} + (\frac{\omega_1}{s})^2}\right| \tag{2.2}$$

$$\left|H_L(s)\right| = \left|\frac{1}{1 + \frac{\sqrt{2}s}{\omega_2} + (\frac{s}{\omega_2})^2}\right| \tag{2.3}$$

$$\left|H_T(s)\right| = \left|\frac{1 + \frac{s}{\omega_3}}{1 + \frac{s}{Q_4\omega_4} + (\frac{s}{\omega_4})^2}\right| \tag{2.4}$$

$$\left|H_S(s)\right| = \left|\frac{1 + \frac{s}{Q_5\omega_5} + (\frac{s}{\omega_5})^2}{1 + \frac{s}{Q_6\omega_6} + (\frac{s}{\omega_6})^2}\left(\frac{\omega_5}{\omega_6}\right)^2\right| \tag{2.5}$$

ISO 2631-1 includes six distinct filters which comprise of a combination of the four filters which are applicable to WBV when analysing either health, comfort, perception or motion sickness.

BS 6841 prescribes a different set of weighting filters. These filters are a combination of a band-limiting filter, that accounts for low pass and high pass filtering, and a frequency weighting filter. Rimmel and Mansfield (2007) show that these filters can be rewritten to represent the filters given by ISO 2631-1.

The filters prescribed by ISO 2631-1 for health analyses are presented in Table 2.1 with the applicable directions and locations. The corresponding BS 6841 filters for measuring on the seat surface are also given. BS 6841 also requires measurements at the seat-back and on the floor beneath the person's feet as well as rotational measurements on the seat surface.

Table 2.1: Weighting filters for health analyses of WBV of seated person

Filter	Standard	Position	Direction	Relevant transfer functions
W_k	ISO	Seat surface	z-axis	$H_H(s)$,$H_L(s)$,$H_T(s)$,$H_S(s)$
W_b	BS	Seat surface	z-axis	$H_H(s)$,$H_L(s)$,$H_T(s)$,$H_S(s)$
W_d	ISO,BS	Seat surface	x,y-axis	$H_H(s)$,$H_L(s)$,$H_T(s)$
W_c	ISO	Seat-back	x-axis	$H_H(s)$,$H_L(s)$,$H_T(s)$

The frequency weighting is implemented by either applying the different filters sequentially or by calculating the product of the different filters. The parameters prescribed by ISO 2631-1 for each of the filters are presented in Table 2.2 with the values for W_b as calculated by Rimmel and Mansfield (2007). G is the filter gain that is multiplied into the product of the filter components. The f values given in Table 2.2 are frequencies in Hz. The filter equations however require that the frequencies are in radians per second. These frequencies are converted to radial frequency by Equation 2.6.

$$\omega = 2\pi f \tag{2.6}$$

Table 2.2: Parameters of filter equations for frequency weighting

Filter	f_1	Q_1	f_2	Q_2	f_3	f_4	Q_4	f_5	Q_5	f_6	Q_6	G
W_k	0.4	0.71	100	0.71	12.5	12.5	0.63	2.37	0.91	3.35	0.91	1
W_b	0.4	0.71	100	0.71	16	16	0.55	2.5	0.9	4	0.95	1.15
W_d	0.4	0.71	100	0.71	2	2	0.63	∞	-	∞	-	1
W_c	0.4	0.71	200	0.71	8	8	0.63	∞	-	∞	-	1

The W_k and W_b filters are used to weigh the acceleration signal in the z-direction for ISO 2631-1 and BS 6841 respectively while W_d weighs the horizontal acceleration on the seat surface. The comparison of the resulting filters is shown in Figure 2.5. It is clear that W_d and W_b have similar shapes and that W_b regards acceleration at higher frequencies to have a greater impact compared to W_d. From this graph it can be seen that the human body is more sensitive to lower frequency vibration in the horizontal directions than in the vertical direction when the person is seated.

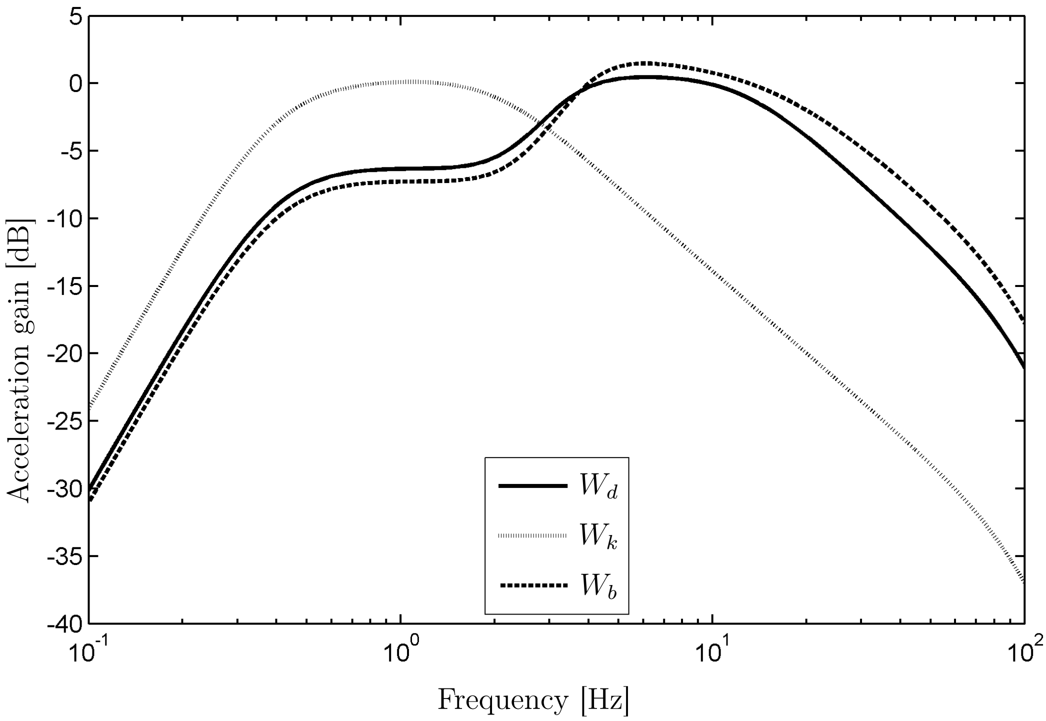


Figure 2.5: Acceleration gain for weighting filters

The methods of BS 6841 and ISO 2631-1 are both used in industry and depends on the location of the tests and the local legal requirements. Even though both standards are used, Directive 2002/44/EC requires all measurements to be performed according to ISO 2631-1. Lewis and Griffin (1998) concludes that BS 6841 is simpler and more logical than ISO 2631-1 and that an improved international standard is required. Due to the global use and general acceptability of ISO 2631-1, this standard will be used for all further WBV analysis in the present work.

2.5 Implementation of human vibration weighting functions

The difficulty with implementing the weighting functions is that the frequencies need to be known to successfully weight the amplitude. ISO 2631-1 advises that the acceleration-time data is divided into one-third octave bands and that the centre value of each band is substituted into the filter equations to obtain a factor. This factor is multiplied by the magnitude of the one-third octave band to obtain a weighted magnitude. Rimmel and Mansfield (2007, 2010) notes that most vibration data is recorded and stored digitally in the time domain. This is advantageous as it allows for trends to be identified. Weighted time data is necessary to calculate the required vibration metrics such as crest factor (CF). This necessitates that filtering has to be done in the time domain.

ISO 2631-1 does not provide any indication of how to implement the weighting functions on digital, time domain data. Rimmel and Mansfield (2007, 2010) propose that each function is converted into an infinite impulse response (IIR) filter. The filter is implemented by using Equation 2.7. $y[n]$ denotes the weighted signal and the $x[n]$ denotes the unweighted signal. n is an index that cycles through all data points. The coefficients a_k and b_j are dependent on the weighting curve. To ease implementation of this, Rimmel and Mansfield (2007, 2010) calculated the coefficients to implement each weighting function into the IIR filter. This was done by using the bilinear transform in Equation 2.8.

$$y[n] = \frac{1}{a_0}\left(\sum_{j=0}^{2} b_j x[n-j] - \sum_{i=1}^{2} a_i y[n-i]\right) \tag{2.7}$$

$$s \to 2\frac{1-z^{-1}}{1+z^{-1}} \tag{2.8}$$

This method requires that the frequency is first normalised and subsequently warped as there is a non-linear correlation between the analogue and digital frequencies. The normalising and warping procedures are shown in Equations 2.9 and 2.10 respectively. These warped frequencies are implemented as parameters into the filter coefficients in Table 2.3. ω_n is the normalised frequency and ω'_n the warped frequency. ω_c is the centre frequency of the filter (from Table 2.2) and ω_s is the sample rate of the data.

$$\omega_n = \frac{2\pi\omega_c}{\omega_s} \tag{2.9}$$

$$\omega'_n = 2\tan\left(\frac{\omega_n}{2}\right) \tag{2.10}$$

Table 2.3: Coefficients for IIR filters

	H_h	H_l	H_t	H_s
a_0	$4Q_1 + 2\omega'_1 + \omega'^2_1$	$4Q_2 + 2\omega'_2 + \omega'^2_2 Q_2$	$4Q_4 + 2\omega'_4 + \omega'^2_n Q_4$	$\frac{4Q_6+2\omega'_6+\omega'^2_6 Q_6}{Q_5}$
a_1	$2\omega'^2_1 - 8Q_1$	$2\omega'^2_2 Q_2 - 8Q_2$	$2\omega'^2_4 Q_4 - 8Q_4$	$\frac{2\omega'^2_6 Q_6-8Q_6}{Q_5}$
a_2	$4Q_1 - 2\omega'_1 + \omega'^2_n$	$4Q_2 - 2\omega'_2 + \omega'^2_2 Q_2$	$4Q_4 - 2\omega'_4 + \omega'^2_4 Q_4$	$\frac{4Q_6-2\omega'_6+\omega'^2_6 Q_6}{Q_5}$
b_0	$4Q_1$	$\omega'^2_2 Q_2$	$\omega'^2_4 Q_4 + 2\frac{Q_4\omega'^2_4}{\omega'_3}$	$\frac{4Q_5+2\omega'_5+\omega'^2_5 Q_5}{Q_6}$
b_1	$-8Q_1$	$2\omega'^2_2 Q_2$	$2\omega'^2_4 Q_4$	$\frac{2\omega'^2_5 Q_5-8Q_5}{Q_6}$
b_2	$4Q_1$	$\omega'^2_2 Q_2$	$\omega'^2_4 Q_4 - 2\frac{Q_4\omega'^2_4}{\omega'_3}$	$\frac{4Q_5-2\omega'_5+\omega'^2_5 Q_5}{Q_6}$

2.6 Evaluation

In order to establish cause-effect relationships between the exposure to WBV and health effects, the WBV has to be quantified by the root-mean-square (RMS) method (ISO 2631-1). This method is not robust when considering impulsive vibration data as it is not sensitive to peaks. For this reason, an additional approach, that is sensitive to peaks, is advised for impulsive vibration.

In addition, ISO 2631-5 can be used to quantify impulsive WBV by approximating the maximum stress in the lumbar spine. All of these analyses are performed after the WBV data has been weighted. The applicability of each method as well as the allowable limits of WBV, as calculated by each method, is discussed in this section.

2.6.1 Basic evaluation

The RMS is the simplest way to calculate a comparable value for vibration. It is a representation of the average level of vibration that is experienced during the duration of the measurement. The RMS is calculated by Equation 2.11. $a_w(t)$ is the weighted time signal and a_w is the RMS of the weighted signal. T is the duration of the measurement. The basic evaluation is applied to each of the measurement axes, x. y and z, independently.

$$a_w = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{\frac{1}{2}} \tag{2.11}$$

It is clear that this approach is applicable only when weighted time data is available. An alternative method of calculating the RMS is presented in Equation 2.12. This method is valid when the measured data is converted to third octave bands and weighted with the method described by ISO 2631-1. The w_i is the weighting value of the centre frequency of each third octave band (as calculated by substituting the frequency into Equations 2.2 to 2.5) and a_i is the unweighted acceleration RMS level in each third octave band.

$$a_w = \left[\sum_i (w_i a_i)^2\right]^{\frac{1}{2}} \tag{2.12}$$

2.6.2 Additional evaluation

In some cases the basic evaluation is not sufficient to quantify the vibration and can lead to the underestimation of the vibration (ISO 2631-1). The additional evaluation methods are aimed at determining metrics that are sensitive to impulsive vibration. Analyses using these methods are performed on each measurement axis independently.

The first method of additional evaluation is the running RMS method. This metric calculates the RMS for smaller time periods. Rather than dividing by the period T, this method divides the integral by the shorter time constant, τ. ISO 2631-1 recommends a value of 1 s for τ. Equation 2.13 is used to calculate an array of the running RMS, $a_w(t_0)$, for each increment of τ.

$$a_w(t_0) = \left[\frac{1}{\tau}\int_{t_0-\tau}^{t_0}\left[a_w(t)\right]^2 dt\right]^{0.5} \tag{2.13}$$

This calculation is repeated for all one second increments in the acceleration data. The metric used to quantify the magnitude of vibration is the maximum transient vibration value ($MTVV$). This is defined as the maximum of the running RMS values as calculated in Equation 2.14.

$$MTVV = \max\left[a_w(t_0)\right] \tag{2.14}$$

The second additional metric is the fourth power vibration dose value (VDV). Here, the fourth power of the weighted acceleration data is used to emphasise peaks in the impulsive time data. The VDV is a dose value which means that it accrues vibration exposure as it increases over time. Any additional vibration that is experienced is added to the VDV up to that point. VDV, with units m/s$^{1.75}$, is calculated by Equation 2.15.

$$VDV = \left[\int_0^T \left[a_w(t)\right]^4\right]^{\frac{1}{4}} \tag{2.15}$$

When more than one measurement is taken the total VDV value can be accrued as in Equation 2.16. The VDV can be estimated in cases where the amount of peaks in the data is limited (ISO 2631-1). Equation 2.17 can be used in these cases to obtain an estimated VDV, the VDV_e. It can be seen that this method assumes a correlation between the VDV and the weighted RMS. Even though BS 6841 and ISO 2631-1 state that VDV_e is suitable if the vibration is not impulsive and does not contain shocks, for pure sinusoidal signals the VDV_e does not estimate the VDV accurately. Integrating the digital data is relatively simple and VDV can be computed rather than VDV_e in most circumstances.

$$VDV_{total} = \left(\sum_i VDV_i^4 \right)^{\frac{1}{4}} \tag{2.16}$$

$$VDV_e = 1.4 a_w T^{\frac{1}{4}} \tag{2.17}$$

2.6.3 Distinguishing between the basic and additional evaluations

ISO 2631-1 recommends that certain ratios can be used to determine whether the basic evaluation is sufficient. The standard stipulates that the basic evaluation provides valuable results even when an additional method is advised.

The first value is the crest factor (CF). It is defined as the ratio between the peak value of the weighted signal and the RMS. The crest factor is used to determine whether RMS is a robust metric to quantify WBV. A high CF is usually indicative of impulsive vibration and can be determined using Equation 2.18. ISO 2631-1 states that a CF greater than 9 warrants the use of the additional methods. This differs from BS 6841 which stipulates the additional method when the CF is greater than 6. Both standards recommend that VDV and $MTVV$ is calculated in these cases.

$$CF = \frac{\max\left|a_w(t)\right|}{a_w} \tag{2.18}$$

In addition to the CF, two other ratios are defined by ISO 2631-1 to determine the validity of the basic evaluation. These two ratios are defined in Equations 2.19 and 2.20.

$$\frac{MTVV}{a_w} \leq 1.5 \tag{2.19}$$

$$\frac{VDV}{a_w T^{0.25}} = \frac{1.4VDV}{VDV_e} \leq 1.75 \tag{2.20}$$

If either of these criteria are not met, ISO 2631-1 advises that the additional evaluation is used to quantify the WBV. Zhao and Schindler (2014) calculated the metrics for operational measurements and found that there are significant changes in the results when the CF is greater than 4.5, the ratio in

Equation 2.19 is greater than 2 and when the ratio in Equation 2.20 is greater than 1.54. In this case, significant changes were described as a difference of greater than 10% between the VDV and the VDV_e. This suggests that the stipulations of ISO 2631-1 and BS 6841 are likely conservative. The crest factor stipulated by BS 6841 is closer to the findings of Zhao and Schindler (2014).

2.6.4 Axis of interest

As the measurement comprised three measurement axes, it is important to note which axis is being analysed. ISO 2631-1 advises that if the vibration, as calculated by the RMS is significantly greater in one axis, only that axis is used to determine the magnitude of the vibration. It does not state what is regarded as significant. In the case that the vibration is comparable in different axes, the vibration total value (VTV), a_v, is to be calculated. Equation 2.21 describes the method in which all three axes are combined. The a_w values are the RMS of each axis calculated by Equation 2.11 while the k values are factors that are direction and application dependent. ISO 2631-1 defines values of k that take into account if the anaysis is performed for health, comfort, perception or motion sickness as well as the posture of the exposed individual.

$$a_v = \left(k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2\right)^{0.5} \tag{2.21}$$

For health applications of seated individuals, the k value for all the axes are given in Table 2.4. This factor is used to account for the cross-axial vibration sensitivity (Figure 2.6). The greater k value for x and y mean that seated humans are more susceptible to lateral vibration. Zhao and Schindler (2014) calculated the vibration in all axes as well as the VTV and found that the use of a single axis can underestimate the vibration even in cases where the different axes are not comparable. For this reason, they advise that the VTV is used in all cases.

Table 2.4: Cross-axial vibration sensitivity for health of seated individuals

Axis	x	y	z
k	1.4	1.4	1

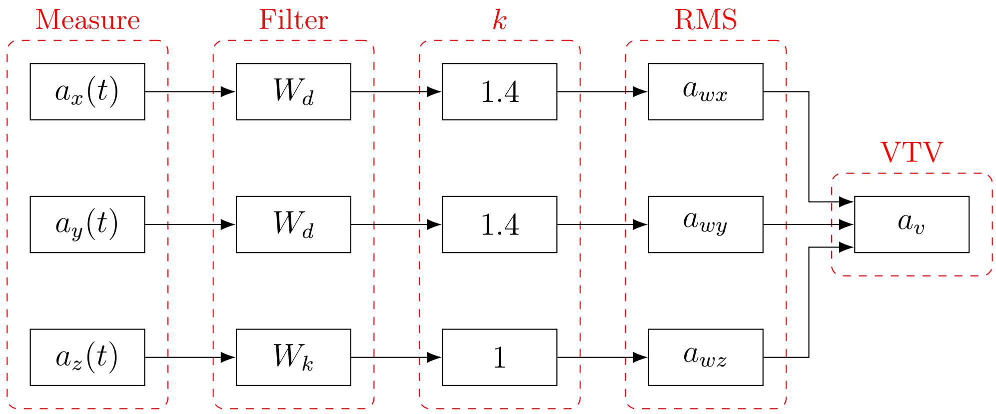


Figure 2.6: Procedure to calculate vibration total value

2.6.5 Analysis of shocks

ISO 2631-5 (International Organization for Standardization, 2004) is a continuation of ISO 2631-1 as it focuses on the impact of WBV on the health of the exposed person. It is focused on the analysis of shocks and notes that there is a strong relationship between dose measurements and health. It is not applicable to single shock events. To allow for ISO 2631-5 to be applicable, the sample rate must be a multiple of 160 Hz. This restriction is due to the modelling of the lumbar spine in the z-direction as a neural network with a sample rate of 160 Hz.

The standard modelled the lateral response of the lumbar spine as a lumped single degree of freedom system. A simplified version of a human spine is depicted in Figure 2.7 with the lumbar spine indicated in purple. The critical damping ratio was found to be 0.22 and the natural frequency to be 2.125 Hz. These values are used to determine the acceleration at the top of the lumbar spine in vertebra L1 ($a_l(t)$) with Equation 2.22.

$$a_l(t) = 5.87(v_s - v_l) + 178(d_s - d_l) \tag{2.22}$$

v_s and v_l are the velocity at the seat and L1 respectively, while d_s and d_l refer to the displacement at the same locations. This algorithm calculates an acceleration-time history of the lumbar spine by extrapolating the measured acceleration on the seat interface.

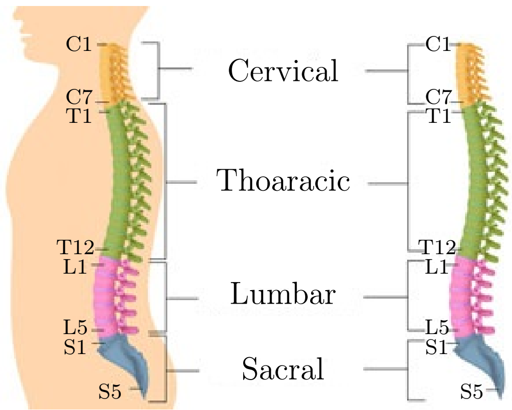


Figure 2.7: Location of the lumbar spine (Nicholson, S.a.)

The spinal response in the z-direction is modelled with a non-linear recurrent neural network. The method of calculating the acceleration time data of the spine is shown in Equations 2.23 and 2.24.

$$a_{lz}(t) = \sum_{j=1}^{7} P_j u_j(t) + P_8 \tag{2.23}$$

$$u_j(t) = \tanh\left[\sum_{i=1}^{4} p_{ji} a_{lz}(t-i) + \sum_{i=5}^{12} p_{ji} a_{lz}(t-i+4) + p_{j13}\right] \tag{2.24}$$

The result of these equations is the time history of the acceleration in the lumbar spine in the z-direction (a_{lz}). The P and p values are constants which model the response of the lumbar spine in the z-direction and is provided by ISO 2631-5. i and j are increments that are used to look up the constants p_{ji}. u_j is calculated by Equation 2.24 for each value of j from 1 to 8 and is substituted into Equation 2.23. The values are dependent on the sample rate and in the case of ISO 2631-5, a sample rate of 160 Hz was used. For this equation to be accurate, all recorded signals in the z-axis have to be re-sampled to this sample rate.

Once all the time histories of the acceleration in the lumbar spine are obtained, a dose value is calculated by means of a sixth power sum as shown in Equation 2.25. In this case p refers to the three different axes, x, y and z. In other words, a dose value for each direction is calculated separately. A_{ip} is peak number i in direction p. ISO 2631-5 stipulates that peak values with a magnitude less than a third of the greatest peak value, are not considered for this evaluation. In the vertical direction, the main contributing factor to health impacts was found to be compressive stress. Compressive stress is created by positive shock vibration and to account for this, only positive peaks $(\max(a_{lz}(t)))$ in the vibration-time data is used. For the lateral directions, all peaks are considered $(\max|a_l(t)|)$.

$$D_p = \left[\sum_i A_{ip}^6\right]^{\frac{1}{6}} \tag{2.25}$$

The three dose values obtained in Equation 2.25 can be combined to result in a static compressive stress, in MPa, in the lumbar spine as calculated in equation Equation 2.26.

$$S_E = \left[(0.015D_x)^6 + (0.035D_y)^6 + (0.032D_z)^6\right]^{\frac{1}{6}} \tag{2.26}$$

2.6.6 Equivalent metrics

As the measurement duration differs between studies, a method is defined to compare values that are independent of measurement duration. a_w and VDV are dependent on time and have to be adjusted to allow for comparability.

The selected method was to adjust all metrics to achieve an equivalent value for an eight hour period ISO 2631-1. The RMS and VDV are respectively adjusted to their eight hour equivalents through Equations 2.27 and 2.28. The equivalent daily exposure for the static compressive stress (S_{E8}) is calculated as shown in Equation 2.29. The equivalent RMS and VDV values are denoted by A_8 and VDV_8 respectively.

$$A_8 = ka_w \left(\frac{T_i}{T_0}\right)^{0.5} \tag{2.27}$$

$$VDV_8 = kVDV \left(\frac{T_i}{T}\right)^{0.25} \tag{2.28}$$

$$S_{E8} = S_E \left(\frac{T_i}{T}\right)^{\frac{1}{6}} \tag{2.29}$$

T_0 is the reference time of eight hours. T is the measurement period and T_i is the duration that the operator is exposed to the task. The unit for all periods have to be the same. The cross-axial sensitivity is taken into account by factor k (Table 2.4). It is possible to rewrite these equations to determine the duration of WBV before a certain level of exposure is reached.

2.7 Limits

No limits to the various metrics are described in ISO 2631-1. It is thus required to use an external source to determine limits for the eight hour exposures calculated in Equation 2.27 and 2.28. Directive 2002/44/EC acknowledges this shortage and therefore set lawfully enforceable limits against which metrics can be compared. The exposure action value (EAV) is defined as the limit that if exceeded, employers must take action to limit the WBV exposure of employees. The exposure limit value (ELV) is defined to set a ceiling for allowable WBV exposure. If the ELV is exceeded, the employer has to stop all operations exposing workers to WBV until the problem is resolved.

ISO 2631-5 stipulates a method to determine whether exposure is likely to cause adverse health effects. It suggests limits associated with allowable lifetime exposure. As the limits are calculated over a lifetime, this method takes into account the age of the person. This is due to a reduction of bone density with age which reduces the ultimate strength of the bone (International Organization for Standardization, 2004; Riggs *et al.*, 2004). The age-dependent bone ultimate strength is calculated in Equation 2.30.

$$S_{ui} = 6.75 - 0.066(b + i) \tag{2.30}$$

Here b is the age at which the person commenced work in an WBV environment and i keeps track of the ageing of the individual. ISO 2631-5 further defines a factor R that assesses the probability of being injured due to WBV. R is calculated in Equation 2.31.

$$R = \left[\sum_{i=1}^{n} \left(\frac{S_{E8} N^{\frac{1}{6}}}{S_{ui} - c} \right)^{6} \right]^{\frac{1}{6}} \tag{2.31}$$

N is the number of days that the person is exposed to WBV per year and c is the stress exerted on the spine by a person's weight. The value of c is given as 0.25 MPa regardless of an individual's weight. The total number of years that a person has been actively exposed to WBV is given by n.

A similar approach to Directive 2002/44/EC of quantifying acceptable limits is given by ISO 2631-5. The R value for which injury becomes probable is 0.8 and the value for which injury is likely, is reported to be 1.2.

ISO 2631-5 further aims to simplify the prediction of WBV injury by defining approximate S_{E8} values that for very specific conditions (starting work at 20 years old and working for 45 years, 240 days a year) may cause injuries. These values (0.5 MPa and 0.8 MPa) are not applicable if the work history of the individual deviates from the standard scenario. For the sake of simplicity and comparability these values will be referred to in terms of EAV and ELV. These EAV and ELV in terms of S_e are used by some authors as set limits to allow comparability with the EAV and ELV defined in Directive 2002/44/EC (Zhao and Schindler, 2014; Gryllias *et al.*, 2016). The EAV and ELV for each of the metrics are tabulated in Table 2.5.

Table 2.5: Exposure action value and exposure limit value for A_8, VDV_8 and S_e according to Directive 2002/44/EC and ISO 2631-5

Metric	Exposure action value	Exposure limit value
A_8	0.5 m/s^2	1.15 m/s^2
V_8	9.1 m/s$^{1.75}$	21.0 m/s$^{1.75}$
S_{E8}	0.5 MPa	0.8 MPa

A popular implementation of these limits is to determine the allowable exposure time before the daily limits are exceeded. If the duration is greater than eight hours, health impacts are unlikely. It can further be used to determine how long an individual can do certain tasks before injury becomes likely in a work environment. As shown by Zhao and Schindler (2014), the use of this method allows for different limits (in terms of A_8, VDV_8 and R) to be compared.

They found that the potential restrictions imposed by the methodology of ISO 2631-5 are more conservative than the analysis given by ISO 2631-1 for operators of compact wheel loaders. Gryllias *et al.* (2016) state that the methods of ISO 2631-1 and Directive 2002/44/EC are more conservative than the methods of ISO 2631-5 for tram drivers. Conservative in these cases means that the EAV and ELV will be reached for the conservative method before the limits for the other analysis method.

To calculate the allowable exposure duration before the EAV is reached (T_{EAV}), Equations 2.32 to 2.34 are used. T is the measurement duration to obtain the VDV and S_e while T_0 is the reference period of eight hours.

$$T_{EAV} = T_0 \left(\frac{0.5}{ka_w} \right)^2 \tag{2.32}$$

$$T_{EAV} = T \left(\frac{9.1}{kVDV} \right)^4 \tag{2.33}$$

$$T_{EAV} = T \left(\frac{0.5}{S_e} \right)^6 \tag{2.34}$$

The difference in the equations are due to RMS being an average measure. Equation 2.32 thus calculates the duration over which the same amount of vibrational energy has to be averaged to obtain a RMS equal to the EAV at eight hours (ISO 2631-1). Some studies have shown that the correlation between RMS values of different durations should be related with a fourth power rather than a power of two (ISO 2631-1). In the duration of interest, namely eight hours, both these approaches give similar results. The assumption of Equations 2.33 and 2.34 is that the measured VDV and S_e are representative of the entire working period of the operator and can be extrapolated over this longer duration.

Similarly, the allowable exposure duration before the ELV is reached (T_{ELV}), is calculated by Equations 2.35 to 2.37. Assuming that the probability of injury is present if any of the T_{EAV} values are exceeded, the most conservative method is to assume that injury is possible after the shortest duration indicated by Equations 2.32 to 2.34. The same applies for T_{ELV} and logic dictates that injury is likely when the smallest T_{ELV} is exceeded by an operator.

$$T_{ELV} = T_0 \left(\frac{1.15}{k a_w} \right)^2 \tag{2.35}$$

$$T_{ELV} = T \left(\frac{21.0}{kVDV} \right)^4 \tag{2.36}$$

$$T_{ELV} = T \left(\frac{0.8}{S_e} \right)^6 \tag{2.37}$$

2.8 Influence of meta-data

Milosavljevic *et al.* (2012) outlines a method of capturing various data in addition to the vibration history. This research recorded demographic data such as work experience, mass, stature and age. Specifics of the conditions, such as terrain and vehicle information, were also recorded. This was achieved through the use of a whole-body vibration health surveillance questionnaire (WBVHSQ). Studies aiming to better understand the influence of the biodynamics of the human body under WBV, such as Rakheja *et al.* (2010), might increase the use of meta-data in future WBV prevention programs.

In addition Milosavljevic *et al.* (2012) recorded the speed of the vehicle and the distance travelled by the vehicle. The results of this study determined that WBV shows a correlation with demographic characteristics of a person and is compounded by the conditions.

2.9 Relevance to South African mining environment

Aye and Heyns (2011) identified from various sources that health and safety concerns arise from exposure to WBV in mining applications. In particular, they noted that WBV is present in South African opencast mines. Even though regulations do exist in numerous countries, South Africa does not have any legislation that governs allowable WBV levels. In the absence of legally enforceable limits, Directive 2002/44/EC can be used to gauge whether WBV levels are problematic.

It was found by Aye and Heyns (2011) that for typical operations in a South African opencast mine, 50% of researched vehicles exceed the EAV, which mandates mitigating actions according to Directive 2002/44/EC. They also identified the prevalence of excessively high CF values with a maximum of 54.78. From this study it can be seen that excavator operators experience impulsive vibration as no crest factors below 10 were measured in any axis. The WBV experienced by only a single excavator exceeded the EAV. For excavator measurements vertical and fore-aft vibration were dominant. Other vehicles of interest are the bulldozers. All measured bulldozers were found to have VDV_8 metrics greater than the EAV for lateral vibration. Only a single vehicle, a Power Star Refueller, was found to exceed the ELV.

Paddan and Griffin (2002) did a comprehensive study comparing the measured WBV vibration for a variety of vehicles. Measurements were repeated on each vehicle type and analysed statistically. The vehicles that were used included cars, lorries, buses, excavators and armoured vehicles. Severe axis RMS and VDV values for some vehicle types are reported in Table 2.6. The measurement duration was one minute in all cases. This means that the results are likely not representative of the WBV experienced by an operator during an average working day. Table 2.6 can however be used to determine a comparison between the WBV levels in different vehicle types. The main vibration axis is not reported for any of the results.

Table 2.6: Median most severe axis WBV exposure in vehicles for 1 minute measurements (Adapted from: Paddan and Griffin, 2002)

Vehicle type	Number of vehicles	a_w (m/s^2)	VDV (m/s$^{1.75}$)
Car	25	0.39	1.51
Excavator	4	0.91	3.55
Lorry	16	0.50	1.96
Armoured vehicle	4	0.85	3.33
Bus	10	0.56	2.17

The median of the excavator measurements presented with a greater a_w and VDV compared to the other vehicle types. Paddan and Griffin (2002) found that greater WBV levels were present in excavators than in any other ground vehicles. However, they did not measure the WBV exposure of bulldozer operators. Combining the findings of Aye and Heyns (2011) and Paddan and Griffin (2002), it can be seen that two vehicle types of importance are excavators and bulldozers in mining applications. Both of which are widely used at Richards Bay Minerals (RBM).

2.10 Conclusion

Even though various standards and regulations exist that guide the analysis of WBV, in some cases the standards are general and cannot account for all circumstances. Lewis and Griffin (1998) states that incorrect WBV measurements can have detrimental economical and humanitarian effects. The further development of scientific knowledge that identifies the shortcomings of the various standards can decrease the social and monetary impact.

A specific point in which researchers do not have consensus, is a suitable measurement duration. Atkinson *et al.* (2002) criticises the approximately 15 minute measurement duration used in most studies. They regard 15 minutes as insufficient to capture a vibration signal that is non-stationary random. Mansfield *et al.* (2003) found that RMS converges sufficiently to be regarded as stationary random for 10 minute measurements. Paddan and Griffin (2002) regard repetitive one minute measurements to accurately capture a representative WBV exposure. ISO 2631-1 states that the chosen measurement duration should be statistically determined to be representative of the WBV. Very few studies, other than Mansfield *et al.* (2003), use statistics to determine a representative duration. Some authors let their measurement durations be dictated by natural stoppages in the studied task (Aye and Heyns, 2011).

The focus of the current study is to expand the method used by Mansfield *et al.* (2003) to determine a suitable measurement duration by statistical methods to quantify the impact of measurement duration on the accuracy of the WBV metrics given by ISO 2631-1. The assumptions of normality used by Mansfield *et al.* (2003) will be evaluated and the method will be expanded to study the impact of measurement duration on the accuracy of VDV. The environment in which these methods will be applied is on vehicles at RBM, an opencast mine in South Africa.

To expand the limited data of WBV exposure in South Africa, the WBV at the mine will be evaluated according to ISO 2631-1 and compared to the limits set by Directive 2002/44/EC. The impact of vehicle type and use on WBV metrics will be explored to determine the impact of these factors. In accordance with these findings, measures to limit the exposure of vehicle operators will be discussed.

Chapter 3

Measurements

Measurements were performed at an opencast mine in the KwaZulu-Natal province of South Africa during October and November of 2016. The mine operates at four individual sites north of Richards Bay. The selection and exclusion criteria, the instrumentation of the vehicle with the Svantek 106 human vibration meter (HVM) and how the measurements were conducted in accordance with ISO 2631-1 is explained.

3.1 Background

The mine extracts heavy minerals from sand dunes by means of wet-mining (Richards Bay Minerals, S.a.a) and a summary of the mining process and the vehicles used for each task is presented in Figure 3.1. This process is also called dredging. Dunes are collapsed into freshwater ponds and the sand is sucked up and concentrated by a concentrator to extract the heavy minerals. Due to this process, the mining face of the dune constantly moves forward. The predominantly mined mineral is ilmenite which is refined to form titanium dioxide (TiO_2), titania slag (Ti) and pig iron ($FeTiO_3$). Secondary minerals that are produced and sold in their raw forms are rutile and zircon (Richards Bay Minerals, S.a.b). A dredging pond is shown in Figure 3.2.

The mine uses heavy mobile equipment (HME) such as bulldozers and excavators to service the dredging operations that extract the heavy minerals (ilminite, rutile and zircon) from the dunes. To access the areas in which the mining operations occur, off-road 4-wheel drive (4x4) vehicles are used.

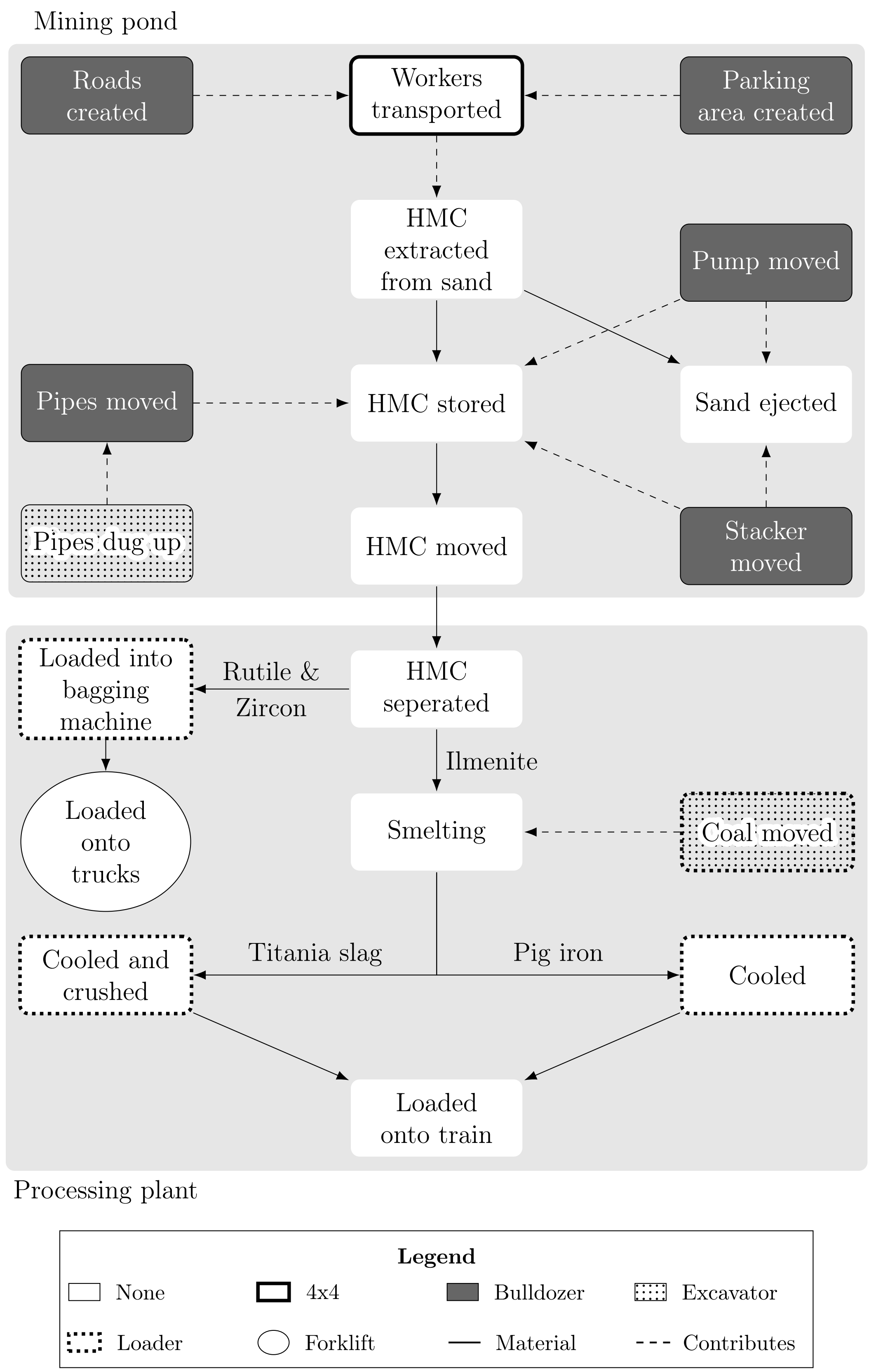


Figure 3.1: Flow chart of mining operations with measured vehicles

Figure 3.2: Overview of dredging pond (Mineral-Loy, 2009)

The extracted minerals are loaded on to trucks that transport the mixture of heavy minerals, also called the heavy mineral concentrate (HMC), to the separation plant. Figure 3.3 presents a photograph of the extracted HMC which is stored in piles until it is transported to the processing plant.

Figure 3.3: Heavy mineral concentrate stacks waiting to be loaded on to trucks

At the separation plant, the minerals are separated by their magnetic properties and the ilmenite is refined further. Titania slag and pig iron are produced by melting the ilmenite and have to be cooled down before further processing can take place. The transportation of the finished pig iron and titania slag is performed by heavy machinery and trains. The zircon and rutile are bagged separately and transported by forklifts on to trucks.

A multitude of peripheral tasks support the mining process such as servicing machinery, logistics and community interaction. One of the significant tasks, is the clearing of vegetation from the dunes by bulldozers and trucks to ease the dredging process. Due to environmental factors, the dunes and vegetation are rehabilitated to a level acceptable to the land owners. The provision and transport of coal products, used mainly for generating heat during the refining process, is partially accomplished by HME. The various tasks contribute to the mining process in varying degrees and mostly occur concurrently.

The climate in Richards Bay can be described as warm with an average temperature of 21.9°C. The area experiences significant rainfall with an annual average of 1123 mm (Climate-Data.org, S.a.). The historical climate data shows that October and November 2016 experienced a combined rainfall of 170 mm and maximum temperatures of 27°C and 28°C respectively (World Weather Online, S.a.). The average humidity over this two month period was 76.5%.

The scope of this project is to analyse specific tasks where vehicle operators are exposed to whole-body vibration (WBV) as identified by the Health and Safety Department. Only tasks that directly contribute to the production process were considered for analysis.

3.1.1 Servicing dredging

The main focus of the present work was the WBV exposure of drivers operating heavy mobile equipment at the mining ponds and servicing the dredging operations. The HME used for these tasks are predominantly bulldozers followed by excavators. Figure 3.4a shows a parked dozer while an excavator digging water pipes out of the ground is shown in Figure 3.4b. The bulldozers are used to create platforms for parking areas, temporary buildings and landing areas for barges on the edge of the pond. In addition, the bulldozers are used for the movement of heavy equipment such as pipes, stackers (that eject the unused sand and HMC), platforms and pumps. The transportation of the pipes is aided by excavators that dig out and bury the pipes before and after they are moved. Finally, the bulldozers are used for the creation and maintenance of roads that allow access to each dredging site.

(a) Bulldozer (b) Excavator

Figure 3.4: HME examples at RBM

The bulldozers are of particular interest as previous research (Aye and Heyns, 2011) has identified that bulldozers in mining environments potentially pose a risk of exposure to high WBV levels. The bulldozers were observed and measurements were performed on a variety of these vehicles with different operators. Due to the relative importance of bulldozers as identified by the staff at the mine and research (Aye and Heyns, 2011) conducted at similar sites, the majority of measurements were focused on these vehicles. In some cases, the exposure for these operations was measured more than once with different operators or vehicles. The impact of a single operator using different vehicles was not explored.

The movement of sand to create platforms or roads and the dragging of pipes were observed frequently. Tasks that require multiple bulldozers working in unison (moving platforms, stackers and pumps) were observed less frequently. The scheduling of these tasks are irregular and difficult to predict as they are scheduled as the need arises.

The excavators were observed and measurements were recorded while they were used to move and dig out pipes. During most of this process, the excavators are stationary and were deemed to be less important than the bulldozers.

3.1.2 Accessing mining ponds

The mine operates in shifts and the workers regularly have to travel to and from the mining ponds. The mine provides transport from the mine offices to the various ponds. The roads travelled are in part asphalt and predominantly sand. Due to the rough nature of the sand roads, they are only accessible by 4x4 vehicles. Figure 3.5 depicts typical surfaces which vehicles need to travel across.

Figure 3.5: Road conditions around the mining pond

The drive from the office to the pond is completed at least twice per day by the HME operators. The employees that oversee the tasks of the HME around the pond travel on the sand roads constantly during the working day.

The rough roads led to the evaluation of WBV experienced by the driver of a 4x4 during the trips to the mine, driving around at the pond as well as the drive back to the offices.

3.1.3 Moving pig iron and titania slag

After the refining process at the processing plant, pig iron bars are transported to a bay where they are cooled with water. Similarly, titania slag is cast into teacup shaped moulds which are transported to a yard where the products are water and air cooled. The cooled blocks are then dropped by HME to break them apart and the smaller blocks are crushed by machinery to form a powder.

Trains transport the titanium powder and slag blocks while a loader is used to drop the blocks. Wheel loaders with special attachments transport the pots in which the pig iron bars are cooled.

The road surface at the slag plant is smooth compared to the conditions experienced around the mining ponds and only one measurement of approximately 30 min was taken on each HME performing these tasks as the vibration was deemed to be stationary random due to the absence of uneven terrain.

3.1.4 Bush clearing and rehabilitation

Bush clearing is the task in which the vegetation and topsoil is cleared from the dunes. This is to ensure that the dredging can take place without any plant material blocking the pipes. The trees and undergrowth is cleared by pushing it over with bulldozers. This task was identified as problematic in terms of WBV by the health and safety staff at the mine. Bush clearing does not contribute to the main production process of the plant and no measurements were taken of vehicles aiding in this task.

After a certain dune has been completely mined, the dune is topographically recreated by stacking waste sand generated by the dredging process. Stackers expel the sand as it is generated during the separation of the sand and minerals. To accurately recreate the dunes, the stackers are moved up to twice per day. Bulldozers are used to push and pull the stacker to position them as necessary.

In addition, the pipes leading from the concentrator to the stacker have to be moved. Booster pumps provide adequate pumping pressure so that the sand and water mixture can reach the stacker. These pumps are heavy and have to be moved as the mine progresses. It requires four bulldozers working in unison to move a single booster pump as shown in Figure 3.6. The leading bulldozers pull the pump with chains while the two trailing bulldozers push the load forward. One measurement on a leading bulldozer as well as a measurement on a trailing bulldozer were obtained.

3.2 Ethical clearance

As the current study consisted of measurements on individuals that are exposed to a hazardous medium, ethical clearance was required. The Stellenbosch University Research Ethics Committee granted clearance for this project according to the stipulations of the Department of Health (2015). The National Health Research Ethics Committee registration number assigned to this project is REC-050411-032.

The conditions of the ethical clearance are, amongst others, that each operator was required to sign a informed consent form, no personal information may be published and that all personal data has to be securely stored.

Figure 3.6: Booster pump moved by four bulldozers

3.3 Instrumentation

The vibration data was captured by the Svantek SV 106 six-channel human vibration meter (HVM) shown in Figure A.1 (Appendix A1). This is a device dedicated to the measurement of WBV and hand-arm vibration. The unit consists of a seat-pad (Svantek SV 38V) and a data acquisition and analysis instrument which adheres to the requirements of ISO 8041 (International Organization for Standardization, 2005).

The instrument records either three or six channels and performs the frequency weighting of human vibration in real time (Sections 2.4.4 and 2.5). Internal memory stores the time data at a sample rate of 6 kHz.

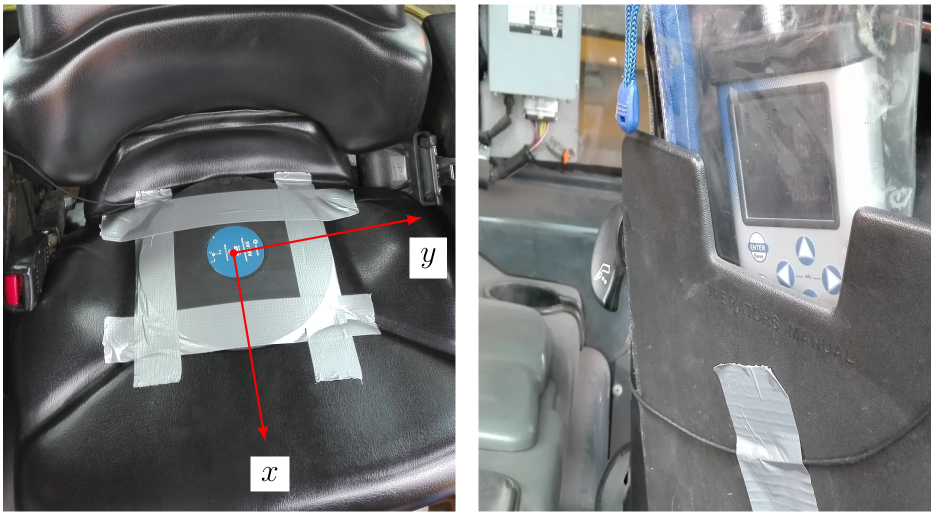
The ISO 2631-1 metrics: a_w, VDV, CF, $MTVV$ and peak acceleration are displayed on the built-in screen in real time. The results of each of these metrics, as well as the acceleration-time data is stored for each axis at the end of the measurement. Data is then transferable to a computer where further analysis is possible. The HVM was calibrated with a Svantek SV 111 calibrator in the Structural Laboratory at Stellenbosch University before the onset of testing.

The seat pad consists of a tri-axial micro-electro-mechanical (MEMS) accelerometer mounted in a lightweight semi-rigid rubber pad that is designed not to influence the stiffness of the seat that it is placed on. Slots in the rubber pad allow for the seat pad to be strapped down. This method proved troublesome as the seat pad was able to move even when fixed to the seat with straps. Duct tape was used to properly attach the seat pad to the seat as shown in Figure 3.7a.

To fix the seat pad and HVM in the correct location, duct tape, scissors, cable ties and a tape measure were used. The cable between the HVM and the seat pad was secured with tape. To protect the HVM from the harsh environment, it was placed in a protective bag (Figure 3.7b). The bag protected the instrument from bumps, sand and scratches. Table 3.1 summarises the instruments used for on-site measurements with their respective serial numbers.

Table 3.1: Instruments

Instrument	Serial Number
Svantek SV 106	36763
Svantek SV 38V	43432
Svantek SV 111	30574



(a) The Svantek SV 38V seat pad fixed to the seat surface using duct tape.

(b) The Svantek SV 106 HVM placed in a protective bag inside the vehicle cabin.

Figure 3.7: Installed measurement instrumentation

3.4 Data captured

As an ethical consideration, each individual operating a vehicle was asked to complete a document stating that they are aware of the risks involved and still wish to participate in the research (Appendix A2).

The main method of data capture was directly with the Svantek SV 106 HVM. It was used to store the weighted acceleration-time data at 6 kHz in all three basicentric axes from a seat pad accelerometer attached to the seat surface. The final results (at the completion of each measurement) for a_w, VDV, CF, $MTVV$ and peak acceleration were stored on the device. To ensure the accuracy of the data and to allow customised calculations, the time data was stored.

A measurement field sheet, presented in Appendix A3, was used to capture the relevant meta-data. This data includes the vehicle identifier, the date, measurement duration and the task conducted. Additionally, any significant events such as visible shocks, breaks taken by the operator and changes in the operating conditions were recorded in the notes section of the sheet. For every vehicle that was instrumented, a new vehicle field sheet was completed that contained all the particulars of the vehicle.

The information captured on this sheet includes the vehicle type, make, model, seat condition, wheel or track type and the direction in which the driver faces relative to the driving direction. Appendix A4 contains an example of this sheet.

3.5 Method

In order to perform an on-site WBV measurement, it was firstly necessary to obtain permission from the shift manager. The measurement process, goal of the research and possible risks were then explained to the drivers. If the operator agreed to participate in the measurement, they were required to complete the informed consent form in Appendix A2. No driver particulars were recorded in accordance with the granted ethical clearance.

The vehicle was approached and the make, model and identifier were recorded on the vehicle field sheet. The seat condition was checked and it was noted whether the vehicle drives on wheels or tracks. The seat of the vehicle was then cleaned to ensure that the seat pad can be fixed to the seat.

To ensure that the accelerometer was in the correct position, the middle of the seat was determined through measurement with a tape measurer (in the lateral direction). The correct location was determined by sitting down and marking the position of the ischial tuberosities on the seat. The middle of the seat pad was placed on this marker. The direction of the x-axis was checked to be correct by placing a ruler on the indicated x-axis on the seat pad and ensuring that the ruler passes over the centre of the seat. The pad was secured in place with four strips of duct tape as shown in Figure 3.7a.

A suitable location for the HVM was identified for each vehicle. This position greatly varied between types of vehicles as in bulldozers the cabin has small storage spaces. The pouch on the seat-back in Figure 3.7b, in which the HVM is an example of a typically used storage location. Most other vehicles do not have space to place the HVM and in these cases it was taped to the body of the vehicle. The cable connecting the seat pad to the HVM was taped down to minimise the possibility of measurement noise (Figure 3.7b).

The measurement was initiated on the HVM as well as on a wristwatch. The vehicle was then cleared and the operator climbed into the vehicle. The time (on the wristwatch) at which the operation started was recorded on the field sheet. The vehicle was observed for the duration of the measurement (whenever it was possible) and all changes in conditions were recorded.

Once the task was completed, the driver switched off the vehicle, climbed out and signalled that the work was completed. The measurement was then stopped on the HVM and the instruments were removed from the cabin. The duration as well as the VDV, a_w and CF was recorded on the field sheet.

Chapter 4

Analysis

The vibration exposure of 22 individual vehicles were measured, in 32 different measurements, and analysed. All analyses were done according to ISO 2631-1 using custom software written in Matlab. Whole-body vibration (WBV) metrics, as calculated by the software, were compared to the metrics reported by the human vibration meter (HVM) to validate the calculation process. The risk of injury due to WBV was assessed according to the limits set out in Directive 2002/44/EC. Meta-data captured for each measurement was compared to the eight hour WBV exposure to aid in establishing cause-effect relationships. Factors that contribute to high levels of WBV were identified and noted to aid in the development of intervention plans.

4.1 Overview

Five types of vehicles were studied in terms of their respective WBV exposure. The categories were bulldozers, excavators, 4x4 passenger vehicles, loaders and forklifts. The time data stored on the Svantek SV 106 HVM was analysed using Matlab code to calculate the ISO 2631-1 metrics including a_w, VDV, $MTVV$ and CF. These metrics were calculated over the measurement period for each axis individually.

An assumption of an eight hour work day was used to calculate the equivalent metrics A_8 and VDV_8 which were compared to the respective exposure action value (EAV) and exposure limit value (ELV) to determine the risk involved in operating each vehicle. These equivalent metrics, as well as the T_{EAV}

and T_{ELV} for VDV and root-mean-square (RMS), were further determined for each axis. The minimum value of T_{EAV} for the three axes was used to determine the minimum duration for which the vehicle can be operated safely. For each vehicle, the axis with the highest vibration was reported.

4.2 Verification

Calculated WBV metrics, as computed by the Matlab code, were compared to the results of the HVM. These calculated metrics were found to accurately represent the data captured by the Svantek SV 106. The results generated by the code and the HVM calculated metrics are compared for a measurement on a bulldozer making a new parking area in Table 4.1. The absolute error (Equation 4.1) is reported for each case.

Table 4.1: Error of Matlab code by comparison of WBV metrics of a bulldozer

	a_w (m/s^2)			VDV (m/s$^{1.75}$)			CF		
	x	y	z	x	y	z	x	y	z
Matlab	0.284	0.257	0.431	4.676	3.323	7.216	13.06	10.23	29.42
Svantek	0.284	0.257	0.432	4.688	3.334	7.244	13.06	10.26	29.48
% Error	0	0	0.232	0.257	0.331	0.388	0	0.293	0.204

$$\%\text{Error} = \frac{|\text{Matlab} - \text{Svantek}|}{\text{Svantek}} \times 100\% \tag{4.1}$$

The maximum absolute error between the respective metrics is 0.388%. This error is present in the calculation of the VDV in the z-direction with the calculated VDV being slightly greater. The metrics reported by the HVM are regarded as the correct value for each error calculation. The mean error of the Matlab code for this measurement is 0.189%. The maximum- and mean absolute error for each measurement are compared in Figure 4.1. The maximum of all measurements is the error made in the z-direction a_w for a measurement on a 4x4 passenger vehicle. The error of 0.549% is due to the low a_w (0.183 m/s^2) so that a error of 0.001 m/s^2 has a great influence on the absolute error.

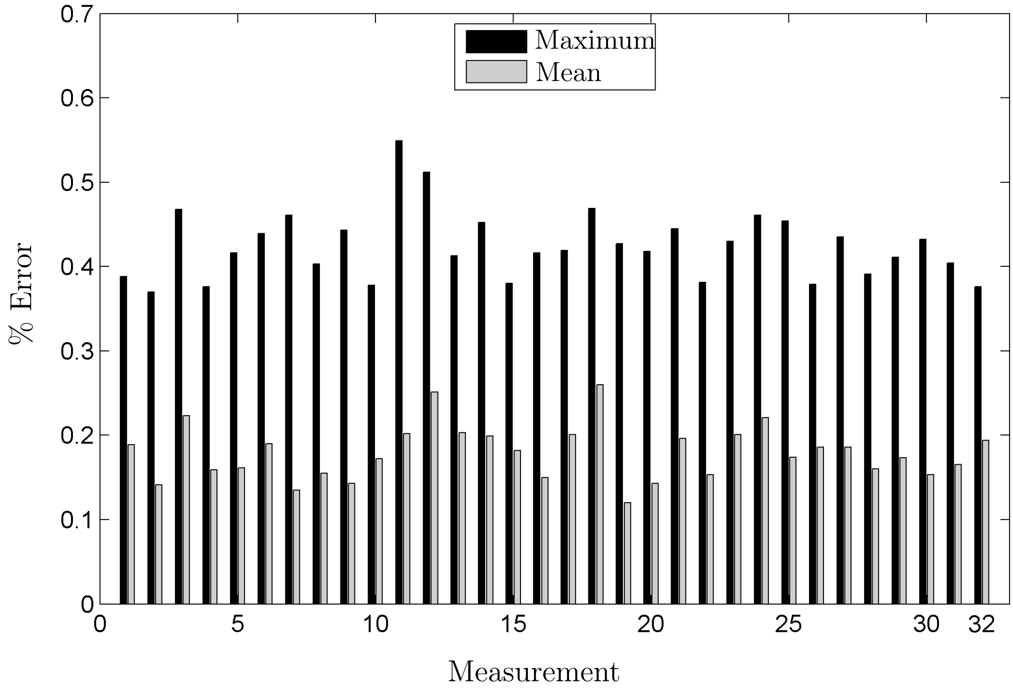


Figure 4.1: Maximum and mean error of Matlab code for WBV metrics

Digital measurements of data are pre-disposed to measurement error. The magnitude of the error is dependent on the sample rate and the bits used to capture the digital magnitude. The intrinsic error present in digital measurement instruments partially arises from quantisation-, saturation- and conversion errors (Figliola and Beasley, 2011). The allowable errors for a human vibration meter amounts to more than 25% (ISO 8041). Some of the allowable error components include frequency weighting (12.2%), sensitivity (3.5%) and linearity (8%). In light of these comparatively high percentages, it was concluded that the Matlab code calculates WBV metrics with sufficient accuracy.

4.3 Whole-body vibration metrics

a_w and VDV were used to calculate the equivalent eight hour metrics as well as the allowable exposure time. The weighted time data of a measurement on a Toyota Land Cruiser shows that the character of a WBV acceleration-time signal is non-stationary and random (Figure 4.2). In this case, the maximum peak acceleration was recorded in the lateral direction. The periods during which the vehicle was stationary are indicated.

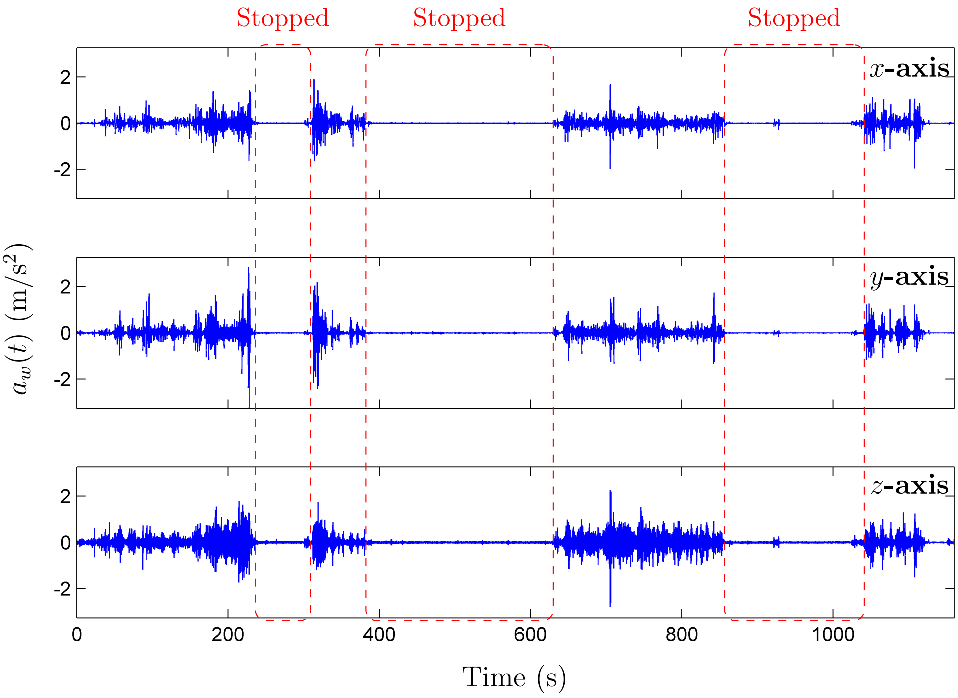


Figure 4.2: Weighted acceleration-time data for Toyota Land Cruiser

4.3.1 Basic evaluation

In order to gauge the vibration present in all measurements the basic evaluation of WBV was used (Section 2.6.1). The weighted time data was downloaded from the HVM and analysed to obtain weighted RMS values (a_w) for each measurement in the x, y and z-axes. When assuming that the measurement is representative of the vibration experienced by the operator and that the total exposure duration is eight hours, T_0 and T_i cancel out and A_8 is equal to ka_w (Equation 2.27). As a result of this, the directly calculated a_w multiplied by the cross-axial sensitivity value, k, is used as the equivalent daily exposure, A_8.

A_8 for each measurements is reported in Table 4.2. It was found that nine bulldozers (60%) and three loaders (50%) exceed the EAV. No other vehicles exceeded the EAV and no vehicles were identified with A_8 greater than the ELV. A Caterpillar D7R bulldozer creating a new parking area (measurement 3) experienced the highest daily equivalent RMS of 0.91 m/s^2. This corresponds to a T_{EAV} of 2.4 h and T_{ELV} of 12.8 h.

Table 4.2: WBV results for all measurements

Measurement	Vehicle type	Make and model	Task	Measurement duration (min)	A_8 (m/s^2)			VDV_8 (m/s$^{1.75}$)			Axis	T_{EAV} (h)	T_{ELV} (h)
					x	y	z	x	y	z			
1	Bulldozer	Caterpillar D7R2	Bulldoze sand	74.0	0.40	0.36	**0.43**	10.44	7.42	**11.51**	z	**3.1**	>24
2	Bulldozer	Komatsu D85PX	Bulldoze sand	44.3	0.58	0.52	**0.75**	14.72	12.16	**15.17**	z	**1.0**	>24
3	Bulldozer	Caterpillar D7R	Bulldoze sand	156.3	0.62	0.48	**0.91**	17.28	12.13	**21.22**	z	**0.3**	**7.7**
4	Bulldozer	Caterpillar D7R	Bulldoze sand	128.3	0.33	0.22	**0.46**	12.18	6.49	**13.67**	z	**1.6**	>24
5	Excavator	Caterpillar 329D	Move pipes	283.3	0.43	0.36	**0.46**	15.80	15.82	**17.55**	z	**0.6**	16.4
6	Bulldozer	Caterpillar D7R	Drag pipes	86.0	0.63	0.55	**0.85**	16.02	12.70	**20.64**	z	**0.3**	8.6
7	Bulldozer	Caterpillar D7R2	Move stacker	112.3	0.24	**0.27**	0.12	21.83	**24.32**	13.41	y	**0.2**	**4.4**
8	Bulldozer	Komatsu D85PX	Bulldoze sand	281.2	0.24	0.27	**0.31**	9.27	8.84	**13.61**	z	**1.6**	>24
9	4x4	Toyota Land Cruiser	Drive	64.3	0.34	**0.41**	0.41	9.79	**12.03**	11.91	y	**2.6**	>24
10	4x4	Toyota Land Cruiser	Drive	23.3	0.31	**0.38**	0.37	8.57	**10.56**	10.10	y	**4.4**	>24
11	4x4	Toyota Land Cruiser	Drive	31.3	0.36	**0.43**	0.41	6.76	**6.94**	5.39	y	23.7	>24
12	4x4	Toyota Land Cruiser	Drive	19.1	0.20	**0.23**	0.18	6.72	**9.83**	5.11	y	**5.9**	>24
13	4x4	Toyota Land Cruiser	Drive	11.3	0.24	**0.32**	0.20	9.32	**11.44**	12.29	z	**2.4**	>24
14	4x4	Toyota Land Cruiser	Drive	7.3	0.37	0.40	**0.44**	9.19	9.69	**11.18**	z	**3.5**	>24
15	Excavator	Caterpillar 329D	Move pipes	303.1	0.26	0.20	**0.28**	8.15	6.82	**9.73**	z	**6.1**	>24
16	Bulldozer	Caterpillar D7R2	Move platform	171.3	0.35	0.35	**0.72**	11.01	9.26	**17.40**	z	**0.6**	17.0
17	Bulldozer	Caterpillar D7R2	Drag pipes	88.3	0.34	0.35	**0.89**	10.17	8.36	**22.95**	z	**0.2**	**5.6**
18	Bulldozer	Caterpillar D7R	Move pump	179.9	0.41	0.37	**0.67**	11.89	9.63	**22.88**	z	**0.2**	**5.7**
19	Bulldozer	Caterpillar D8R	Move pump	78.3	**0.45**	0.37	0.39	11.97	8.45	**18.06**	z	**0.5**	14.6
20	Bulldozer	Caterpillar D7R2	Bulldoze sand	331.3	0.39	0.38	**0.79**	12.28	10.17	**21.49**	z	**0.3**	**7.3**
21	Bulldozer	Caterpillar D7R2	Drag pipes	384.3	0.38	0.38	**0.56**	12.84	9.95	**16.87**	z	**0.7**	19.2
22	Bulldozer	Caterpillar D7R2	Drag pipes	377.9	0.33	0.34	**0.41**	11.23	10.36	**13.39**	z	**1.7**	>24
23	Bulldozer	Caterpillar D7R2	Drag pipes	352.3	0.33	0.32	**0.72**	10.18	8.40	**19.01**	z	**0.4**	11.9
24	Loader	Kawasaki 85ZV	Move coal	129.1	0.63	**0.69**	0.47	**15.55**	15.30	12.34	x	**0.9**	>24
25	Excavator	Hitachi Zaxis 200	Move coal	134.3	0.22	0.22	**0.34**	6.77	8.02	**18.17**	z	**0.5**	14.3
26	Loader	Caterpillar 226B	Move coal	36.9	**0.84**	0.49	0.81	18.98	13.03	**27.53**	z	**0.1**	**2.7**
27	Loader	Komatsu WA800	Move titania	125.3	0.59	**0.64**	0.35	15.43	**15.98**	9.65	y	**0.8**	23.9
28	Loader	Kress P240CSE	Move iron	28.3	0.36	**0.49**	0.21	**14.07**	10.48	7.77	x	**1.4**	>24
29	Loader	Bell B35D	Move iron	111.3	0.17	0.16	**0.27**	7.09	5.62	**11.90**	z	**2.7**	>24
30	Forklift	TCM 45	Load bags	27.1	0.23	0.23	**0.36**	5.54	5.33	**8.52**	z	10.4	>24
31	Forklift	Clark C45	Load bags	79.3	0.23	0.20	**0.46**	6.19	6.56	**13.96**	z	**1.44**	>24
32	Loader	Bell L1204E	Move zircon	22.3	**0.42**	0.38	0.27	**10.96**	9.20	8.57	x	11.3	>24

Values in bold indicate the axis with highest exposure and times below eight hours

The main axis of RMS for twenty of the vehicles (62.5%) was in the vertical (z) direction. All the excavator operators and 86.7% of bulldozer operators experienced the most vibration in this direction. The most prevalent direction of vibration for the 4x4 vehicles was in the lateral (y) direction.

Vibration for each measured bulldozer model is compared in Figure 4.3. This figure presents the average A_8 value from all measurements on the vehicle along with error bars associated with the standard deviation (σ). Caterpillar D7R2 bulldozers had the highest average A_8 of 0.82 m/s^2. Most of the work performed with Caterpillar D7R2 bulldozers have vibration levels above the EAV when the RMS values are considered. The model that had the least WBV is the Caterpillar D8R. Only one measurement was performed on this model and as a result no statistically sound conclusions can be made.

Neither of the average A_8 exposures of the excavator models exceeded the EAV (Figure 4.4). The average measured vibration on the Caterpillar 329D is higher than that of the Hitachi Zaxis 200. It can be concluded that the majority of excavators exposed to these circumstances will have vibration levels below the EAV.

Figure 4.5 shows that most of the 4x4 vehicle measurements had an A_8 below the EAV. These six measurements were performed on the same vehicle and the reported exposure accurately represents the WBV as can be concluded from the narrow spread of results.

Neither of the forklifts experienced daily RMS higher than the EAV while loading bags on to a truck (Figure 4.6) while half of measured loaders exceeded it (Figure 4.7). Single measurements were captured for each of these vehicles.

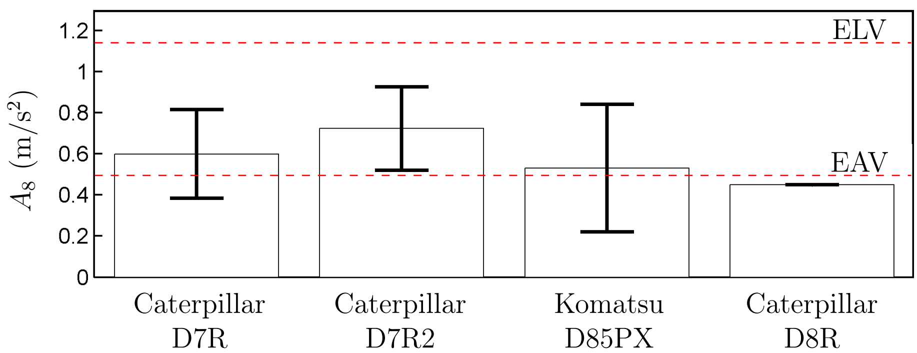


Figure 4.3: Average bulldozer A_8

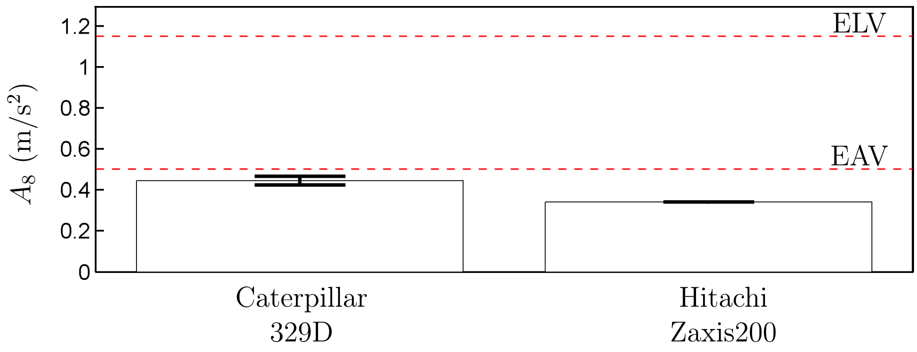


Figure 4.4: Average excavator A_8

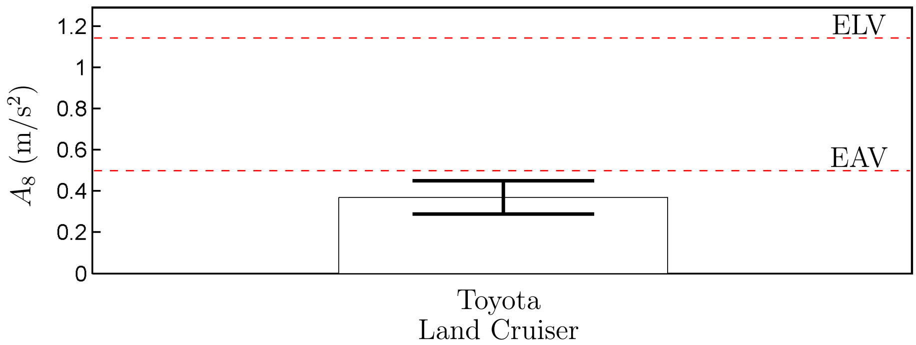


Figure 4.5: Average 4x4 A_8

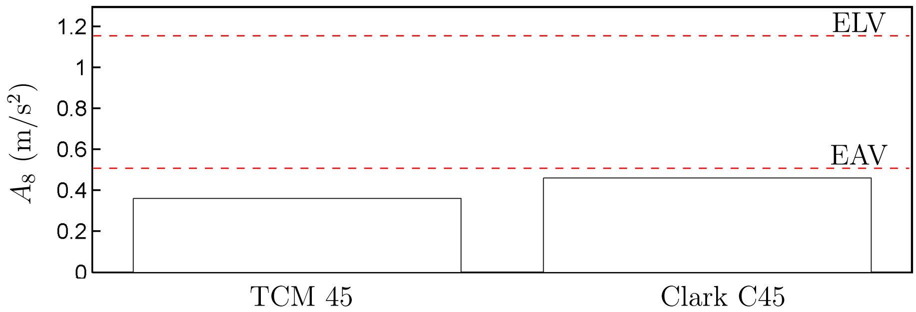


Figure 4.6: Average forklift A_8

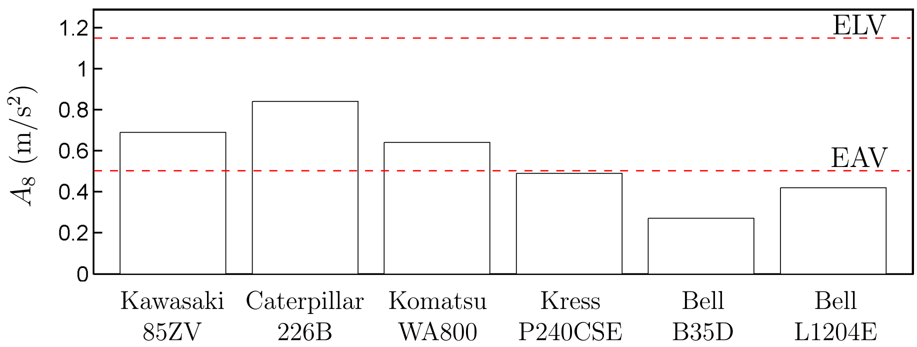


Figure 4.7: Average loader A_8

4.3.2 Applicable evaluation method

The metrics used to distinguish between the basic and additional methods are compared for each measurement in Table B.1. The $\frac{1.4VDV}{VDV_e}$ ratio shows that only measurement two (2) can be evaluated using the basic evaluation method and RMS values. Using the CF or $\frac{MTVV}{a_w}$ as a selection criteria, all measurements have to be analysed by the additional evaluation method. The use of the additional method is therefore applicable to all measurements owing to impulsive vibration.

4.3.3 Additional evaluation

VDV was calculated for each measurement as part of the additional evaluation. The results were grouped by vehicle type and compared to the EAV and ELV of 9.1 m/s$^{1.75}$ and 21.0 m/s$^{1.75}$ respectively (Directive 2002/44/EC). In each case, the highest VDV_8 (Equation 2.28), irrespective of direction is reported. The corresponding axis to this measurement is also indicated. This maximum VDV_8 was used to calculate the time before the EAV and ELV is reached (Equations 2.33 and 2.36). VDV_8, the axis of importance and the corresponding T_{EAV} and T_{ELV} are reported in Table 4.2.

Out of the 32 measurements, only three measurements, on a Toyota Land Cruiser, a Bell L1204E loader and a TCM 45 forklift, had maximum VDV_8 values below the EAV. This is a concern as this amounts to 91 % of measurements experiencing actionable levels of WBV at the mine. A third of bulldozers experienced vibration levels above the ELV which implies that work must stop until action is taken to reduce WBV. Furthermore, a Caterpillar 226B skid steer loader was also found to have a VDV_8 greater than the ELV while moving coal on a smooth cement surface. This loader had the highest recorded VDV_8 of all vehicles with 27.53 m/s$^{1.75}$ in the z-axis.

The predominant axis of highest VDV_8 was the z-axis for bulldozers, excavators and forklifts. The y-direction contributed most in terms of VDV for 4x4 measurements while loaders had no clear problematic axis.

Bulldozer VDV_8 is compared in Figure 4.8. Caterpillar D7R2 bulldozers showed the highest average VDV_8. It can be seen that some operations using Caterpillar D7R and D7R2 bulldozers exert their operators to WBV levels exceeding the ELV. The model with the lowest average VDV_8 is the Komatsu D85PX. All measured bulldozers exceeded the EAV. It is clear that bulldozers regularly expose operators to unhealthy levels of WBV as defined by Directive 2002/44/EC.

The average VDV_8 for both excavator models exceeds the EAV (Figure 4.9). The Hitachi Zaxis 200 experienced a higher VDV_8. It is seen that most excavators exposed to these circumstances will have actionable vibration levels between the EAV and the ELV.

Figure 4.10 shows that most of the 4x4 passenger vehicle measurements had a VDV_8 in the caution zone between EAV and ELV. In some cases the vehicle vibration was below the EAV.

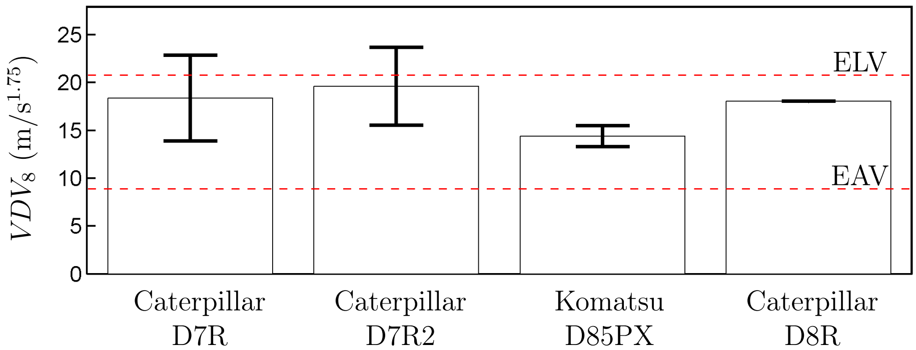


Figure 4.8: Average bulldozer VDV_8

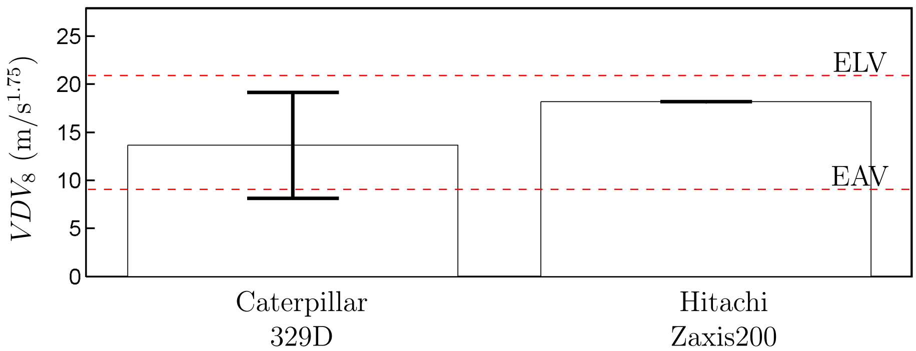


Figure 4.9: Average excavator VDV_8

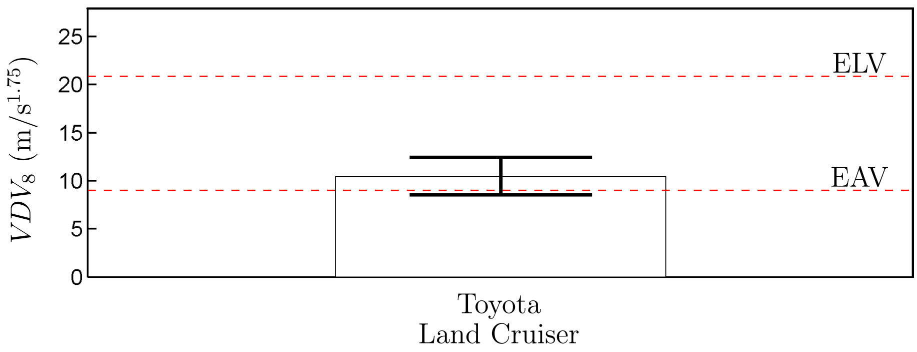


Figure 4.10: Average 4x4 VDV_8

The Clark C45 forklift exceeded the EAV for VDV_8 while the TCM 45 forklift showed vibration exposure slightly below the EAV (Figure 4.11). All loaders exceeded the EAV (Figure 4.12) and the Caterpillar 226B loader had the greatest VDV_8.

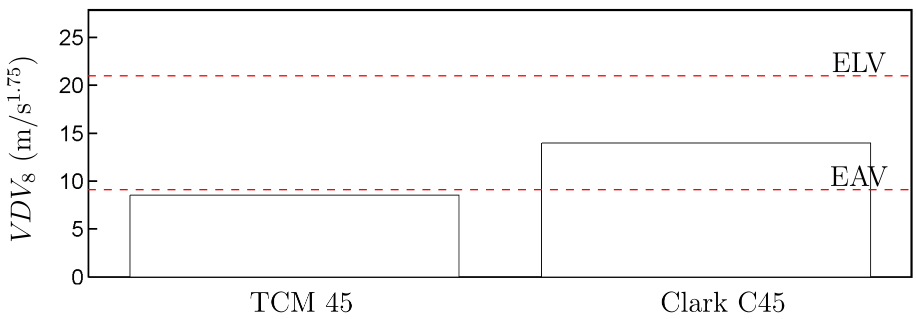


Figure 4.11: Average forklift VDV_8

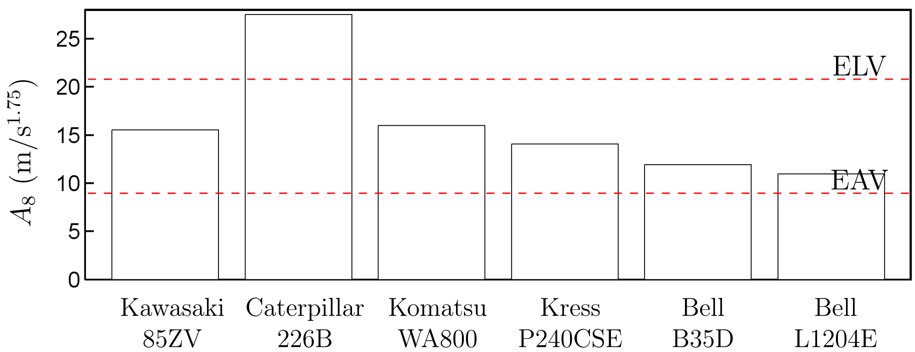


Figure 4.12: Average loader VDV_8

4.4 Influence of operating conditions

To establish the correlation between operating conditions and the measured daily equivalent VDV, vehicle types were grouped to limit variation which can be attributed to vehicle type. The main tasks performed by bulldozers are bulldozing sand to create roads and parking areas, dragging pipes and moving heavy structures such as stackers and pumps. The exposure of the bulldozer operations are compared to the other vehicles and operations in Table 4.3.

Table 4.3: Comparison of WBV exposure for measured tasks

Vehicle type	Task	VDV_8 (m/s$^{1.75}$)			Deviation		
		x	y	z	x	y	z
Bulldozer	Moving sand	12.7	9.5	16.1	2.9	2.4	4.2
	Dragging pipes	12.1	10.0	18.6	2.5	1.8	3.7
	Moving structures	12.1	12.9	17.9	5.1	7.6	3.9
Excavator	Digging out pipes	12.0	11.3	13.6	5.4	6.4	5.5
	Moving coal	6.8	8.0	18.2	-	-	-
4x4	Driving	8.4	10.1	9.3	1.3	1.8	3.2
Loader	Moving coal	17.3	14.2	19.9	2.4	1.6	17.7
	Moving titanium	15.4	16.0	9.7	-	-	-
	Moving iron	10.6	8.1	9.8	4.9	3.4	2.9
	Loading Zircon	11.0	9.2	8.6	-	-	-
Forklift	Loading bags	5.9	5.9	11.2	0.5	0.9	3.8

The daily equivalent vertical VDV of the bulldozers are compared in Figure 4.13. The average VDV_8 for bulldozing sand is the lowest while moving structures had the highest daily equivalent VDV with an average slightly lower than the ELV. It can be assumed that just under half of all vehicles moving heavy structures will expose the operator to WBV levels above the ELV.

4.5 Observations

Some problems in the effective prevention of health impacts on heavy mobile equipment (HME) operators were observed during the course of the project. From a institutional standpoint, guidelines are in place to aid in the continued health of all operators. This includes training on how to properly adjust vibration seats, regular medical surveillance and maintenance of HME.

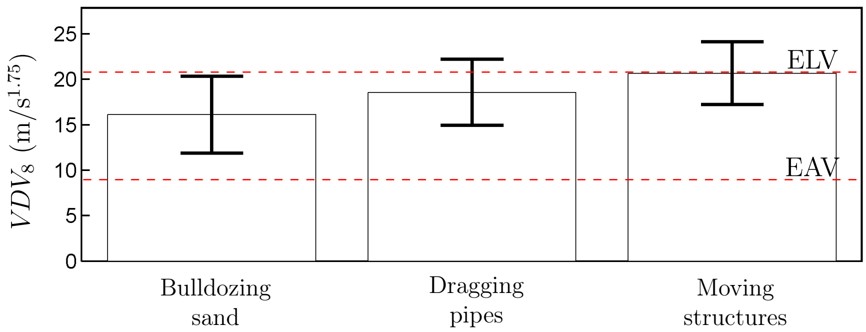


Figure 4.13: Influence of task on bulldozer VDV_8

There are some aspects that are not properly managed. Operators regularly jump from the cabs of HME after a completed shift. The impact from landing can cause spinal injuries due to reduced balance (Mani *et al.*, 2010). Operators driving HME that are dragging pipes are constantly required to twist in their seats to maintain visual contact with the pipes. This posture reduces the ability of the spine to absorb vibration and can increase the risk of injury. Proper posture should also be maintained when the operator climbs into and out of the vehicle.

The impact of driving over a pipe with a bulldozer and through a ditch with an excavator is shown in Figure 4.14. The high magnitude events cause high VDV readings and contribute significantly to the risk involved. The VDV for the 5 s events are 6.1 m/s$^{1.75}$ and 4.3 m/s$^{1.75}$ respectively.

Even though operators are trained, suspension seat settings are rarely adjusted before work begins and it can be assumed that suspension seats are not properly tuned. The adjustment of seats should be added to a standard operating procedure. Shift managers have to ensure that these guidelines are followed. Some seats are in bad condition and the quality of the suspension components are unknown (Figure 4.15). Regular maintenance of all parts that aid in the reduction of WBV is recommended. Suspension seats are effective in reducing vertical vibration and is present in all vehicles except the forklifts, some loaders and the 4x4.

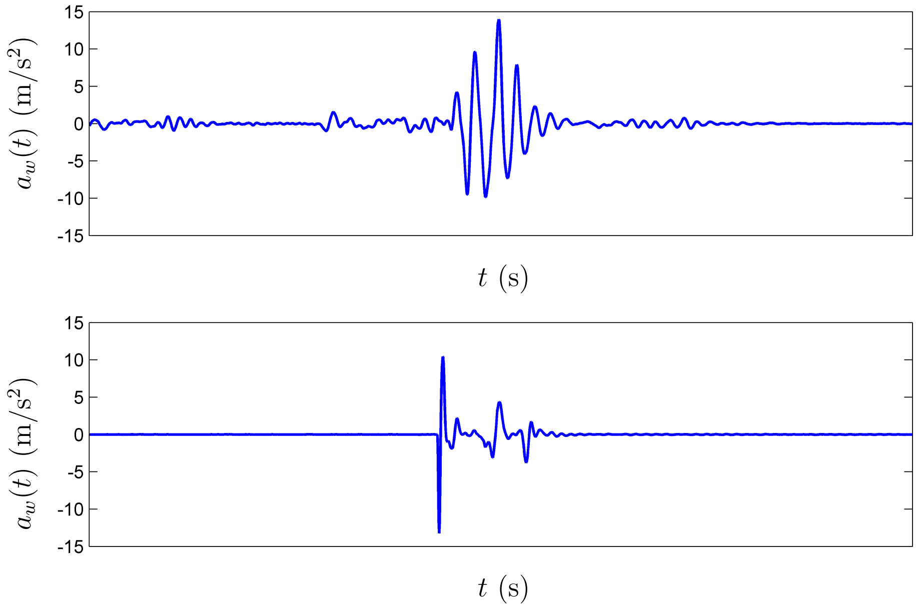


Figure 4.14: Impact of bad driving surface on WBV of a bulldozer and a forklift

Figure 4.15: Condition of suspension seat

4.6 Discussion

The z-axis was the main axis of vibration for the majority of measurements. Basic WBV analysis showed that 12 of the 32 measurements (37.5%) exceed the EAV. High CF and additional ratios proved that the WBV is impulsive for all measured vehicles and RMS is insufficient to calculate whether the EAV and ELV was exceeded. The additional method identified 29 measurements (90.6%) that exceeded the VDV_8 EAV while six measurements (18.8%) exceeded the ELV. WBV is therefore a problem at Richards Bay Minerals (RBM) and have to be addressed.

The difference between these analyses are attributed to the impulsiveness of the WBV. The majority of vibration occurs at low amplitudes with occasional shocks. The low amplitude vibration decreases the overall RMS due to the averaging nature of the metric. VDV gives a better representation as it is not averaged out.

Bulldozers proved problematic as all tested vehicles exceeded the EAV in the z-axis. Vertical vibration can be improved by the proper tuning of the HME suspension seat to isolate the operator from the vibration. Another method is to adjust driver behaviour to avoid uneven driving surfaces. The simplest method to decrease the WBV exposure of operators is to limit the amount of time spent operating problematic vehicles such as the Caterpillar 226B loader.

Loaders and bulldozers appear to be the main contributors to unhealthy levels of WBV at RBM. Moving heavy machinery such as booster pumps and stackers is the main concern for bulldozer operators. These tasks do not occur on a daily basis and operators are not regularly exposed to these conditions. Job rotation can be used to decrease the possibility of health impacts by distributing unhealthy tasks among employees. The inherent risks involved in these tasks should be clearly communicated to all operators.

Situations that compromises operator health should be avoided to decrease the prevalence of spine trauma. Drivers have to be educated on proper posture while driving, as well as procedures to avoid road conditions that can cause shock vibration. The proper management of WBV is critical for the well-being of HME operators at opencast mines.

Chapter 5

Measurement duration study

In the writing of procedures for whole-body vibration (WBV) measurements, the question could be asked: What measurement duration is required to obtain an accurate reflection of the WBV exposure for a working day. ISO 2631-1 requires measurement durations to be sufficiently long to capture WBV that is statistically representative of an entire working day. Due to the non-stationary nature of WBV in a mining environment, great care should be taken to ensure accurate and representative results. The inaccurate measurement of WBV can cause impaired health of operators or unnecessary expenses addressing conditions that have no impact on unhealthy levels of WBV. It is hypothesised that impulsive WBV requires measurement durations greater than 30 min for sufficient accuracy.

5.1 Method

Due to the application dependent nature of WBV, very little literature can be found that quantify an applicable measurement duration. Mansfield *et al.* (2003) determined that a 10 min measurement duration accurately captures the root-mean-square (RMS). No mention is made on a suitable duration to accurately capture the vibration dose value (VDV). The impact of increasing measurement duration on the accuracy of RMS and VDV is studied by assuming that the data is normally distributed as well as for cases that no normal distribution is present. The results of these analyses serve to advise a suitable measurement duration for WBV measurements on vehicles in opencast mines.

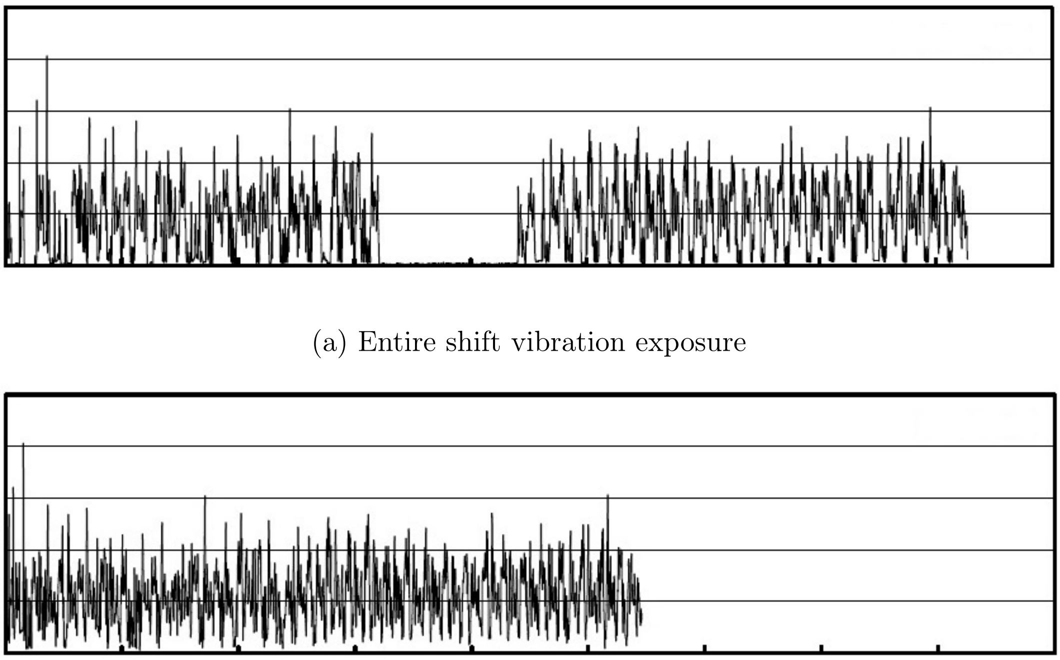
The appropriate measurement duration was investigated by performing WBV measurements for a full working shift to determine the true daily equivalent RMS and VDV values. Sub-sets of this full data record were progressively selected and the WBV metrics for each subset was calculated. The daily equivalent RMS and VDV was compared to the true daily exposure.

5.2 Review of Mansfield *et al.* (2003)

Mansfield *et al.* (2003) establishes an evidence based approach to determine a suitable measurement duration for WBV. This analysis calculated the duration at which the RMS is statistically representative of the daily vertical (z) RMS for 20 vehicles. The measurement duration for each case was selected to capture the entire shift of the operator. The impact of WBV impulsiveness (CF) was not studied and RMS was the only metric used.

The vibration was measured, frequency weighted and the a_w was calculated and logged using a human vibration meter (HVM) for every 10 s interval. It is unclear why 10 s was chosen for the section size. Most HVM allow for this method of logging to visualise the vibration content of shorter time periods. Data segments, containing zero-vibration were removed from the data set to obtain the RMS for all 10 s sections of active WBV exposure (Figure 5.1). The threshold according to which data was deemed to contain no vibration was omitted.

After removing the sections of no vibration, the weighted RMS was calculated by averaging the a_w of all 10 s sections contained within the measurement epoch. The measurement epoch was then propagated through the measurement to calculate an average RMS for each epoch (Figure 5.2). The epoch sizes are 10 s, 30 s, 1 min, 3 min, 10 min, 30 min and 60 min. The RMS of each epoch was plotted against time to visualise the effect of a longer epoch. The increase of epoch size on the variation of RMS is shown in Figure 5.3 for 30 s, 1 min and 3 min epoch sizes. If sections of zero-vibration are not removed, the RMS content of some epoch would be dominated by the lack of vibration energy.



(a) Entire shift vibration exposure

(b) Active vibration exposure

Figure 5.1: Removal of periods with zero vibration. Adapted from Mansfield *et al.* (2003)

It is clear that the variation in RMS decreases as the epoch size increases. This means that a measurement epoch of 3 min has a greater probability of measuring a RMS close to the daily exposure. A measurement epoch was deemed sufficiently accurate if the coefficient of variation (CV) was less than the total allowable error of the HVM (25% according to ISO 8041). The allowable HVM error for frequency weighting, 12.5%, was used to determine a preferable measurement epoch. This approach required that the RMS of each epoch is normally distributed. The exposure metrics for all measured vehicles were found to be sufficiently accurate at a measurement epoch of 10 min while the preferable epoch size determined by Mansfield *et al.* (2003) was 30 min. This indicates that WBV measurements should be performed for longer than 30 min if possible. Any measurement with a duration shorter than 10 min is inaccurate and should be repeated with a longer measurement duration.

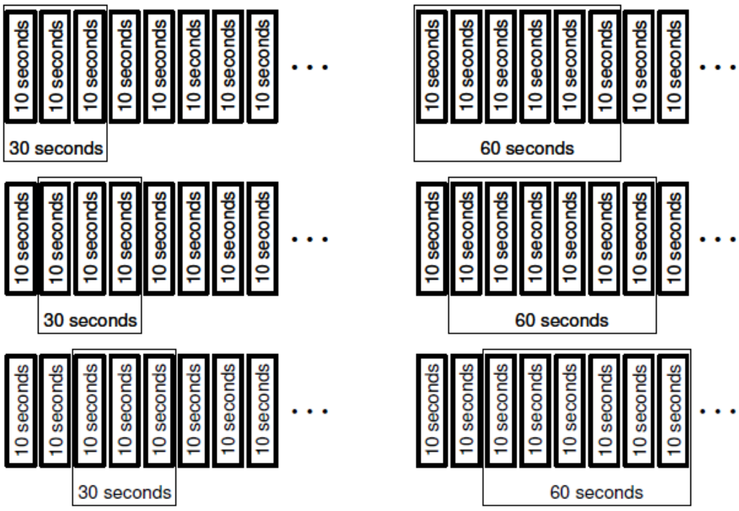


Figure 5.2: Overlapping epochs moving along measurement (Mansfield *et al.*, 2003)

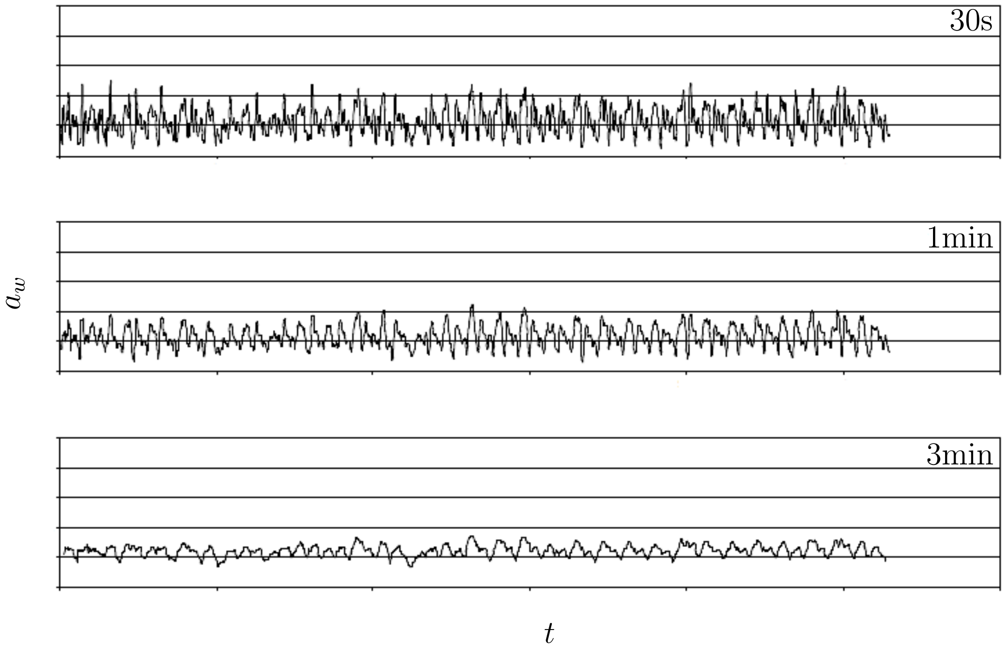


Figure 5.3: Effect of epoch on RMS. Adapted from Mansfield *et al.* (2003)

Off-road vehicles such as excavators and loaders required a longer time than other vehicles for the coefficient of variation to decrease to acceptable levels. This is due to the impulsiveness of the vibration present in off-road vehicles. It was concluded that off-road vehicles required longer measurement epochs for the WBV to be measured accurately. This indicates that the impulsiveness of WBV has a possible impact on the require measurement duration.

5.3 Effect of increasing measurement duration

For the current project, the research done by Mansfield *et al.* (2003) was expanded to include the validation of section size, analyses for impulsive vibration and the testing of normality assumptions. The influence of increasing the section size was studied to determine if the choice of 10 s is optimal. The additional method of quantifying WBV is included to determine if impulsive vibration requires a longer measurement duration to be measured accurately. The normality of RMS and VDV is evaluated and additional methods of quantifying non-normal distributions are explored. For all analyses, the axis with the highest daily equivalent VDV is studied.

The methodology of this study is outlined in Figure 5.4. The acceleration-time data is grouped into subsets called sections and sections deemed to contain no vibration are removed. Sections are in turn grouped into epochs and the WBV metrics of each epoch is compared to the real equivalent daily metrics, VDV_8 and A_8. The accuracy of the epoch WBV metrics are used to advise a suitable measurement duration.

5.3.1 Section size

In the context of this work, section size refers to the duration of data segments for which VDV and RMS values are calculated in order to establish if vibration is present in a section of data or not.

The use of 10s section sizes are unsubstantiated in the analysis done by Mansfield *et al.* (2003). The suitability of a 10 s section size (τ) was established by assuming a section size in the range of 1 s to 20 s in 1 s increments. The RMS and VDV were calculated for each section and sections were deemed to contain zero vibration if the z-axis VDV was lower than 0.1 m/s$^{1.75}$ per second. For example, if the VDV was below VDV_{lim} for a given section size, τ, the section was filtered out (Equation 5.1). The value was found by determining the maximum VDV measured by the HVM without the presence of vibration.

$$VDV_{lim} = 0.1\tau^{\frac{1}{4}} \tag{5.1}$$

The *VDV* and RMS metrics were calculated for each of the channels of the tri-axial seat pad measurements. The z-axis *VDV* for a 10 s section size is compared to the acceleration-time data of a forklift in Figure 5.5. All sections with a *VDV* below the assumed vibration accrual limit of 0.1 m/s$^{1.75}$ are indicated. The sections with zero vibration content are subsequently cut out to obtain the real WBV exposure.

All measurements were segmented with zero-vibration removed and the *VDV* error made by filtering the zero-vibration was calculated for each axis. Figure 5.6 compares the average and standard deviation (σ) of the *VDV* errors for each section size. It is reasoned that the use of section sizes of increased length, would increasingly, blur data resolution and potentially result in the removal of excessive amounts of data. To allow comparability of the results of this study to the results of Mansfield *et al.* (2003), a 10 s section size was used. This assumption is acceptable as no clear superior section size was found in the chosen range. The error made when sectioning and filtering WBV with the chosen section size is less than 1%.

The removal of sections containing no vibration will increase the RMS due to a noteworthy decrease in duration while the vibrational energy stays relatively constant. The impact of this effect is quantified in Table 5.1. The sharp decrease in duration for measurement 7 is attributed to a short high intensity task being conducted. Due to the short exposure time, the high RMS is not problematic as no other work was done during that shift. Due to the short measurement durations of measurements seven, eleven, twelve, thirteen and fourteen (7, 11, 12, 13 and 14) after filtering, they will be excluded from the rest of the duration study.

5.3.2 Measurement epoch

In order to determine the appropriate measurement duration, epochs were chosen as 1 min, 5 min, 10 min, 20 min, 30 min and 60 min. Each epoch was formed by combining sections and using the section RMS and *VDV* metrics to calculate the total epoch RMS and *VDV*. The equivalent daily exposure for each epoch was calculated before the epoch window moved to the next section (Figure 5.2) and the process is repeated.

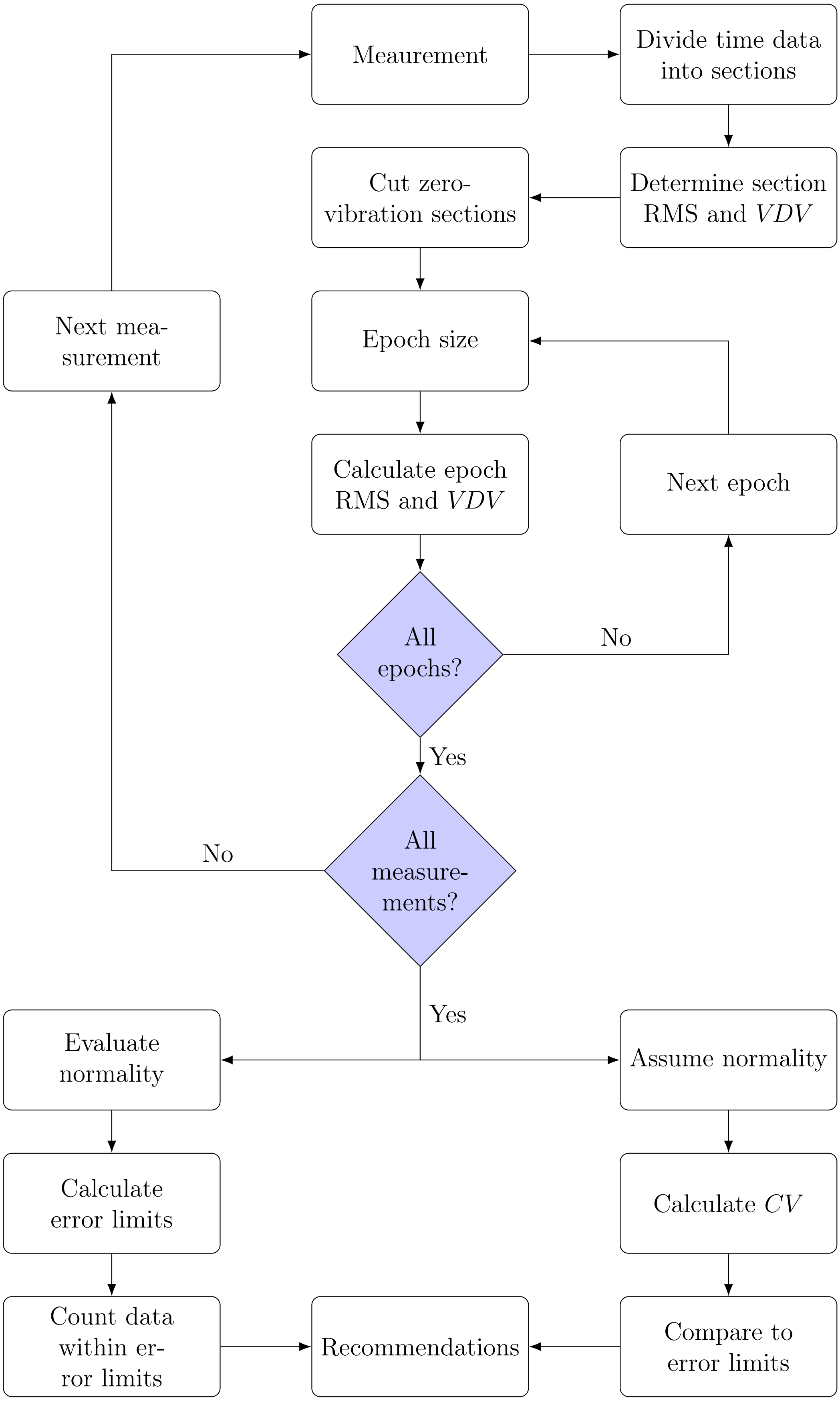


Figure 5.4: Method of analysing measurement duration impact

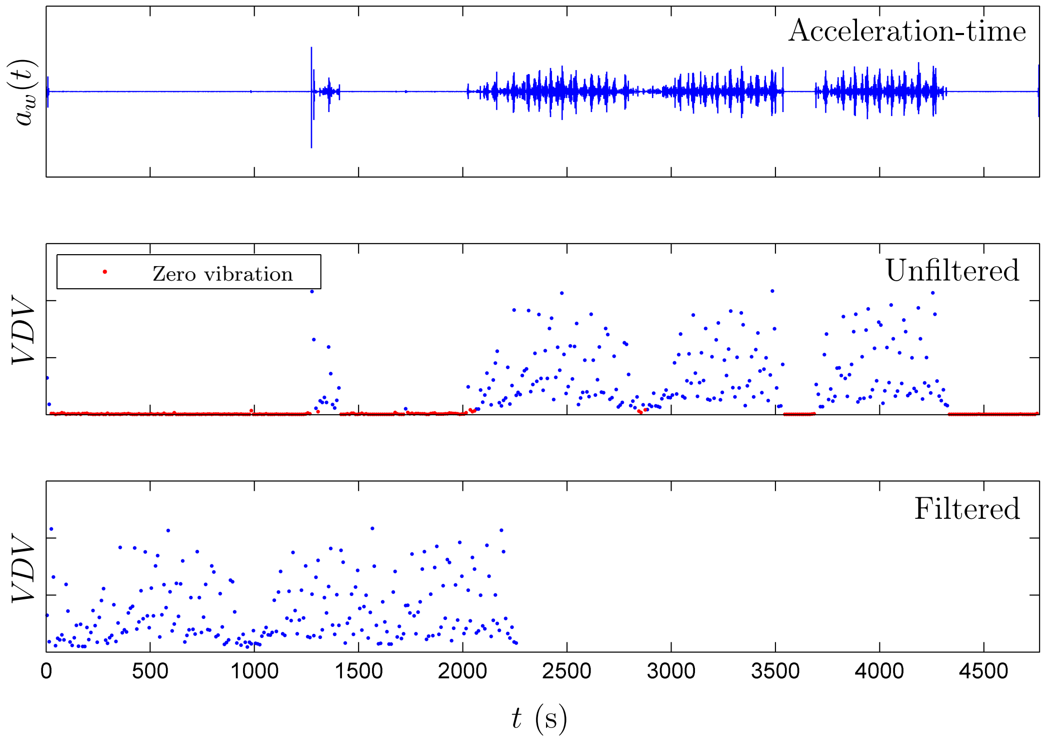


Figure 5.5: Filtering of z-axis VDV for a 10 s section size

The smoothing of epoch RMS is shown in Figure 5.7 and the same behaviour as seen in Figure 5.3 can be observed. The daily equivalent VDV follows the same trend and the values for a greater measurement epoch better represents the real daily equivalent VDV as calculated by the HVM (Figure 5.8).

5.4 Suitable epoch size

Assuming that the VDV and RMS has a normal distribution for all epoch sizes and vehicles, an analysis of the coefficient of variance was conducted. This aimed to evaluate whether 10 min and 30 min are sufficient to achieve measurement accuracy of 25% and 12.5% respectively for impulsive WBV.

The assumption of normality was then tested and an alternative method of determining a suitable epoch size for non-normal distributions is provided.

Table 5.1: Effect of filtering WBV on measurement duration and RMS

	Duration (s)		RMS (m/s^2)	
Measurement	Unfiltered	Filtered	Unfiltered	Filtered
1	4435	3615	0.37	0.45
2	2655	2505	0.67	0.73
3	9375	6195	0.68	1.02
4	7695	2405	0.25	0.76
5	16995	7325	0.24	0.52
6	5155	4245	0.67	0.81
7	*6735*	*25*	*0.02*	*2.7*
8	16865	5465	0.18	0.52
9	3855	2515	0.19	0.28
10	1395	885	0.19	0.29
11	*1875*	*645*	*0.09*	*0.23*
12	*1145*	*605*	*0.14*	*0.25*
13	*675*	*565*	*0.26*	*0.31*
14	*435*	*435*	*0.39*	*0.39*
15	18185	7395	0.16	0.37
16	10275	5835	0.50	0.87
17	5295	3915	0.69	0.92
18	10795	7475	0.46	0.65
19	4695	3685	0.32	0.40
20	19875	10295	0.53	1.01
21	23055	12565	0.38	0.68
22	22675	8775	0.25	0.60
23	21135	11095	0.44	0.82
24	7745	6735	0.39	0.44
25	8055	4175	0.18	0.33
26	2215	1975	0.68	0.77
27	7515	4705	0.33	0.51
28	1695	1655	0.20	0.20
29	6675	1395	0.09	0.42
30	1625	1345	0.38	0.33
31	4755	2255	0.25	0.51
32	1335	805	0.20	0.32

5.4.1 Normally distributed data

The coefficient of variation , CV (Equation 5.2), as defined by Mansfield *et al.* (2003) was calculated for each time epoch. The results for the coefficient of variation, CV, in terms of VDV and RMS are shown for all vehicles in Tables B.2 and B.3 respectively (Appendix B2).

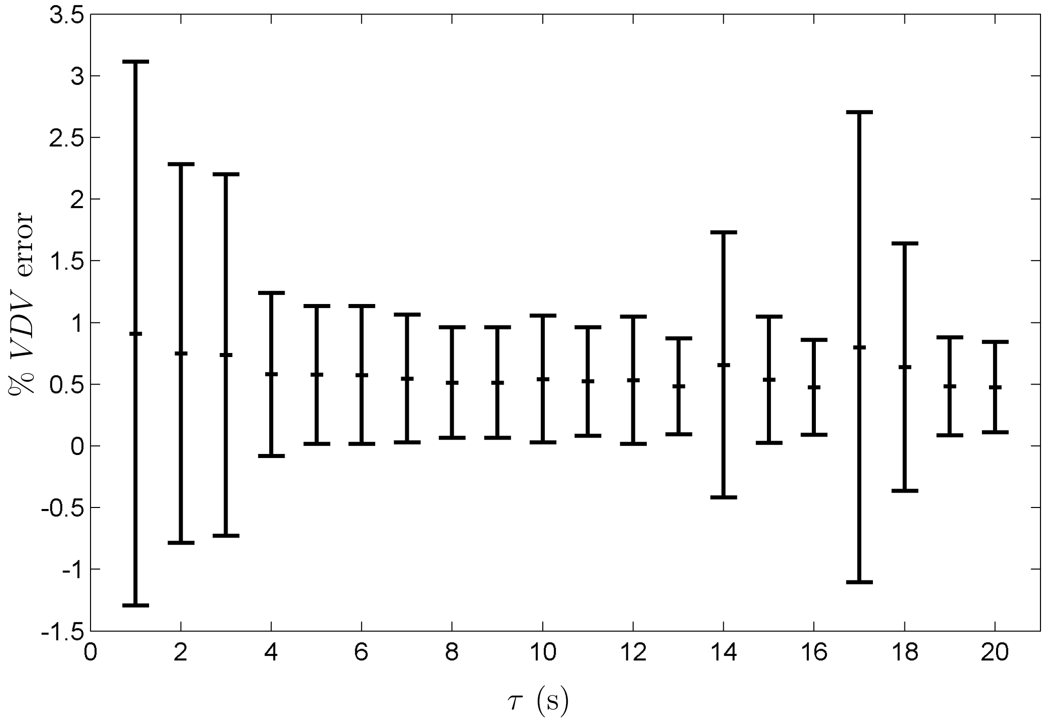


Figure 5.6: VDV error for section size choices

$$CV = \frac{\sigma}{mean} \tag{5.2}$$

A sufficient accuracy (less than 25% error) and a preferable accuracy (less than 12.5% error) is achievable for some cases with 1 min and 5 min measurement durations respectively. In contrast, other measurements require a measurement duration of 60 min for preferable accuracy. For all measurements, an error of less than 25% was made for a 60 min epoch size.

No link between the CV for RMS and VDV is apparent. Measurement five (5) reaches a sufficient accuracy level in terms of RMS before VDV. Some other measurements require a smaller epoch size for VDV than for RMS to be sufficiently accurate.

The epoch sizes stated by Mansfield *et al.* (2003) as accurate are not applicable in all cases. An epoch size of 10min would render inaccurate results in 25.9% of cases in terms of VDV and in 22.2% of cases in terms of RMS. 30 min measurements would lead to insufficient accuracy in 7.4% of measured cases.

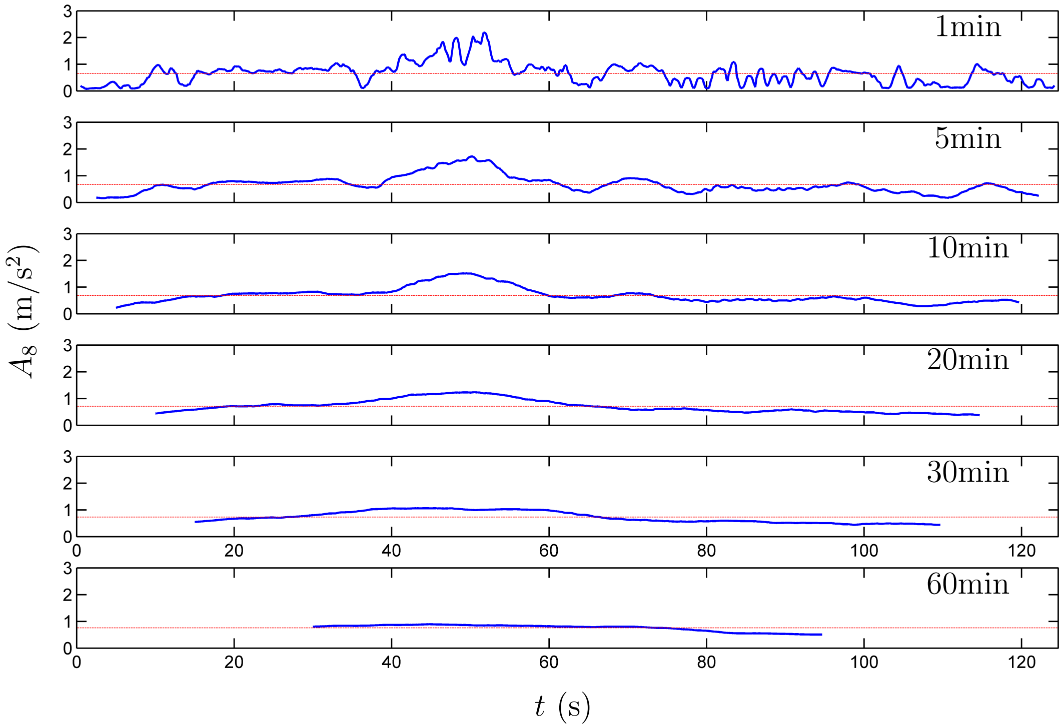


Figure 5.7: Effect of epoch size on the RMS for a bulldozer

5.4.2 Non-normally distributed data

The use of CV for evaluation depends on the normality of the data (Mansfield *et al.*, 2003). Using the one-sample Kolmogorov-Smirnov normality test (Öztuna *et al.*, 2006), it was found that neither of the metrics have normal distributions for any measurement or epoch size at a significance level of 95%. An alternative method of evaluating the accuracy of a chosen epoch size is required.

For a normal distribution, approximately 68% of data points are within one standard deviation from the mean. The problem can be rephrased to state that sufficient accuracy is reached when 68% of data points lie within 25% error bounds of the mean and within 12.5% for preferable accuracy.

To achieve this, limits were set at 25% greater and less than the mean and the percentage of data points that fall within these limits was calculated. If this percentage exceeded 68%, the epoch size was deemed as sufficiently accurate. The process was repeated with limits set at 12.5% from the mean to determine which epoch sizes achieved a preferable accuracy.

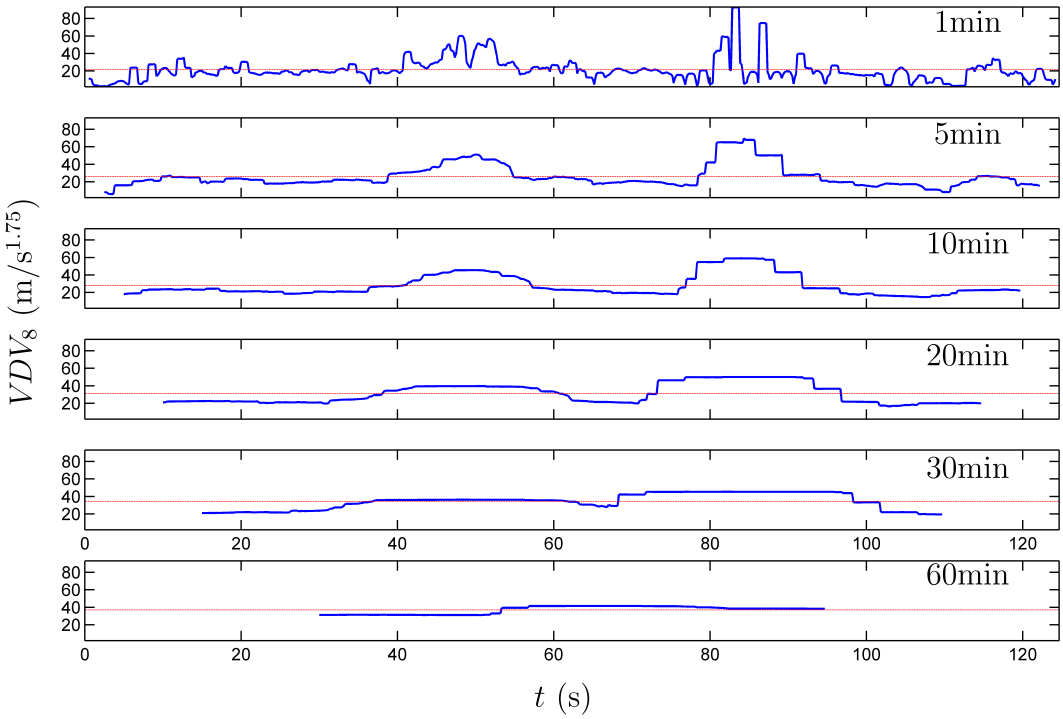


Figure 5.8: Effect of epoch size on VDV for a bulldozer

Figure 5.9 depicts the spread of RMS and the location of the error bounds. The epoch size was deemed accurate if more than 68% of all points fall between the lines. The average RMS for this case is 0.67 m/s^2.

The percentage of data points falling between the limits are shown in Tables B.4 to B.7 (Appendix B3). The percentage data between 25% for RMS and VDV have similar trends. RMS requires a greater epoch size to capture the WBV accurately compared to VDV.

An epoch size of 10 min would render inaccurate results in 18.5% of cases in terms of VDV and in 16.2% of cases in terms of RMS. 30 min measurements would lead to insufficient accuracy in 22.2% of VDV and 25.9% of RMS cases.

5.5 Advised measurement duration

The data showed similar results for preferable epoch sizes whether normality was assumed or not. It is clear that for some cases, none of the epoch sizes will yield accurate results to the required level.

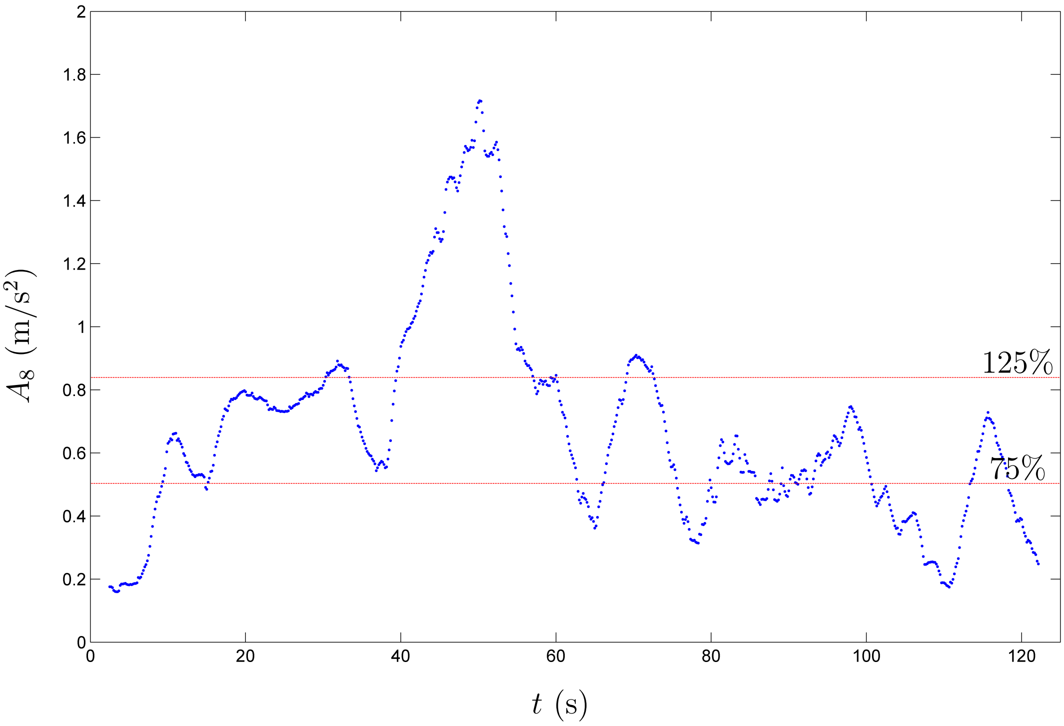


Figure 5.9: Data within error limits

The relationship between epoch size and accuracy is compared in Figure B.1 for each measurement. This figure indicates the minimum required measurement duration to capture RMS and VDV to either a 12.5% or 25% accuracy.

A 60 min measurement duration is sufficient in capturing accurate WBV data for most cases. The normality assumption can lead to overly short measurement durations in some cases. The same trend is observed for non-normality where the required measurement duration is underestimated. For this reason, neither method is superior for all WBV cases.

The cases that required the longest measurement durations (measurements 5, 18 and 21) all have short periods of very high or very low vibration exposure compared to the majority of the vibration. This means that the required measurement duration for accurate results increases if uncharacteristically high or low magnitude vibration events are present.

The vehicles were grouped according to type and the accuracy of the selected epoch sizes evaluated on the group as a whole according to the non-normal method (Section 5.4.2). The percentage of data that was deemed suitably accurate for each vehicle type and each epoch size is compared in

Tables 5.2 to 5.5. It is important to note that the 100% given in the tables are rounded and it does not mean that all measurement of this duration will be accurate. It is however highly probable that these measurements are accurate.

Table 5.2: Percentage of data 25% from mean *VDV* for vehicle types

	Data between limits (%)					
Vehicle type	1min	5min	10min	20min	30min	60min
Bulldozer	62	72	76	82	86	100
Excavator	47	50	53	66	94	100
4x4	39	63	82	100	100	-
Loader	53	80	95	100	100	100
Forklift	48	79	98	100	100	-

More than 68%

Table 5.3: Percentage of data 12.5% from mean *VDV* for vehicle types

	Data between limits (%)					
Vehicle type	1min	5min	10min	20min	30min	60min
Bulldozer	37	42	44	58	67	79
Excavator	22	25	21	39	60	76
4x4	20	32	40	74	100	-
Loader	29	51	75	88	92	100
Forklift	19	43	75	100	100	-

More than 68%

Table 5.4: Percentage of data 25% from mean RMS for vehicle types

	Data between limits (%)					
Vehicle type	1min	5min	10min	20min	30min	60min
Bulldozer	52	64	74	79	84	89
Excavator	46	66	72	87	95	100
4x4	41	73	92	100	100	-
Loader	61	81	96	100	100	100
Forklift	35	48	81	100	100	-

More than 68%

Table 5.5: Percentage of data 12.5% from mean RMS for vehicle types

	Data between limits (%)					
Vehicle type	1min	5min	10min	20min	30min	60min
Bulldozer	28	41	48	54	56	72
Excavator	24	31	38	52	67	93
4x4	20	55	61	98	100	-
Loader	32	52	68	88	93	100
Forklift	13	23	50	90	100	-

More than 68%

Using the results of Tables 5.2 to 5.5, a minimum measurement duration to accurately measure RMS and *VDV* is advised for each vehicle type in Table 5.6. To have at least a 68% probability to achieve accurate measurements, the measurement duration has to exceed the given duration. For example, if an accurate measurement with an allowable error of 12.5% is required on a forklift, the measurement duration has to exceed 20 min. Due to the limited variation in measurement conditions, these recommendations are only applicable for vehicles operating at opencast mines under similar conditions. No direct correlation was found between the recommended measurement duration and WBV metrics or the ratios used to identify impulsiveness.

Table 5.6: Advised measurement duration to achieve accurate RMS and *VDV* measurements

	Duration	
Vehicle type	Sufficient accuracy	Preferable accuracy
Bulldozer	10 min*	60 min
Excavator	30 min	60 min
4x4	10 min	20 min
Loader	5 min	10 min
Forklift	10 min*	20 min*

*Value calculated from RMS

Chapter 6

Conclusion

This study assessed whole-body vibration (WBV) exposure of bulldozers, excavators, 4x4 passenger vehicles, loaders and forklifts at an opencast mine to identify the prevalence of unhealthy levels of vibration exerted on vehicle operators. The methodologies stipulated by ISO 2631-1 were implemented and the WBV was compared to the legally enforceable (in EU compliant countries) limits set out by Directive 2002/44/EC.

6.1 Summary of results and recommendations

The basic evaluation method assumes stationary random vibration and quantifies WBV exposure in terms of a daily root-mean-square (RMS) value. None of the evaluated vehicles exceeded the daily equivalent RMS exposure limit value (ELV) of 1.15 m/s^2 whereas 37.5% of vehicles exceeded the exposure action value (EAV) of 0.5 m/s^2. ISO 2631-1 stipulates the use of an additional method for impulsive vibration that quantifies the vibration as a fourth power vibration dose value (VDV). Analysis according to this method sheds a different light on the measured data. The daily equivalent vibration dose value (VDV_8) analysis identified 29 vehicles (90.6%) that exceed the EAV of 9.1 m/s$^{1.75}$ and six vehicles (18.8%) that exceed the ELV of 21.0 m/s$^{1.75}$. This proves that unhealthy levels of WBV is present and that the health of operators may be potentially impacted by their exposure to shock vibration.

Importantly, all vehicles were found to exert impulsive vibration on the drivers with crest factors (CF) greater than 11 in all measured cases. The additional factors used to identify impulsiveness also indicated the presence of shock vibration. For these reasons, the applicable metric for evaluating compliance to Directive 2002/44/EC is concluded to be the VDV.

The present study found that the WBV is dependent on the type of vehicle. Bulldozers and loaders were identified to be the most likely to over-expose drivers to WBV as summarised in Figure 6.1 by box-and-whisker plots. For bulldozer work, the type of work impacted WBV levels with moving heavy equipment showing the greatest impact. A Caterpillar 226B skid steer loader moving coal on a cement surface recorded the highest VDV and the mitigation of WBV on this vehicle should be explored urgently.

A mitigation program is strongly advised at Richards Bay Minerals to limit excessive WBV. The vehicles that should receive the majority of attention are bulldozers and loaders. As part of the mitigation program, regular WBV assessments in accordance with ISO 2631-1 is required with measurement durations longer than 60 min to ensure the validity of the results. If any doubt exists, the measurement duration should be as long as possible.

To aid in a mitigation program, a field sheet was developed that can provide information on how to mitigate the WBV impact on operators. Bulldozers were found to expose operators to unhealthy levels of vibration in the vertical direction. Properly tuned suspension seats aid in the isolation of an operator from vibration. This seat has to be tuned according to the weight of the operator to function optimally. Proper training in regards to the correct use of these seats will aid in reducing vertical vibration exposure.

The impact of uneven road surfaces on WBV exposure at Richards Bay Minerals was significant. It is recommended that operators are trained to drive with care over obstacles or through ditches. The use of skid steer loaders to move coal was found to be extremely unhealthy. If this task is unavoidable, the operator of this vehicle may only operate this machine for 6 min per day. It is advised that a vehicle with a suspension seat is acquired for this task.

6.2 Suggested measurement duration

It was found that the duration of WBV measurements could potentially have a significant impact on the interpretation of measurement results. The duration of WBV work is influenced by the tasks performed by vehicles where natural breaks may occur during work. Furthermore, worker schedules and breaks influence the practical implementation of measurements. Neither ISO 2631-1 nor Directive 2002/44/EC advise guidelines as to the necessary time required for a representative measurement and there is sparse literature on the subject.

In the light of this background, a suitable measurement duration to accurately capture WBV was investigated. The accuracy of candidate measurement durations were determined by measuring the vibration for a full daily shift and subsequently assuming that only subsets of the full measurement had been captured. The metrics calculated when assuming these subsets were compared to the actual full daily exposure and the percentage error was gauged against the allowable error for a human vibration meter (HVM). The errors were defined as 25% for acceptable accuracy and 12.5% for preferable accuracy. It was found that measurements have to be at least 30 min to capture representative WBV metrics and at least 60 min to measure results with an error lower than 12.5%. The required duration is vehicle dependent and for most vehicles accurate results are achievable with shorter durations. Bulldozers and excavators require the longest measurement duration of 60 min to capture representative data. These results aid in establishing a practice that allows for time efficient and accurate measurements.

6.3 Limitations and future research

The limitations of this research include the small amount of tested vehicles. More cases have to be studied for a greater variety of tasks and vehicle types to achieve statistically significant conclusions. The effect of operating conditions, vehicle speed, engine hours and operator demographics can also be further studied to efficiently advise mitigation programs. The advised measurement durations are only applicable for analyses according to ISO 2631-1 and further research is required to determine a suitable duration for analyses corresponding to ISO 2631-5. All obtained results are exclusively relevant to vehicles of an opencast mine and no conclusions can be made about similar vehicles operating under different circumstances. The influence of CF, RMS and VDV on required duration can also be studied further.

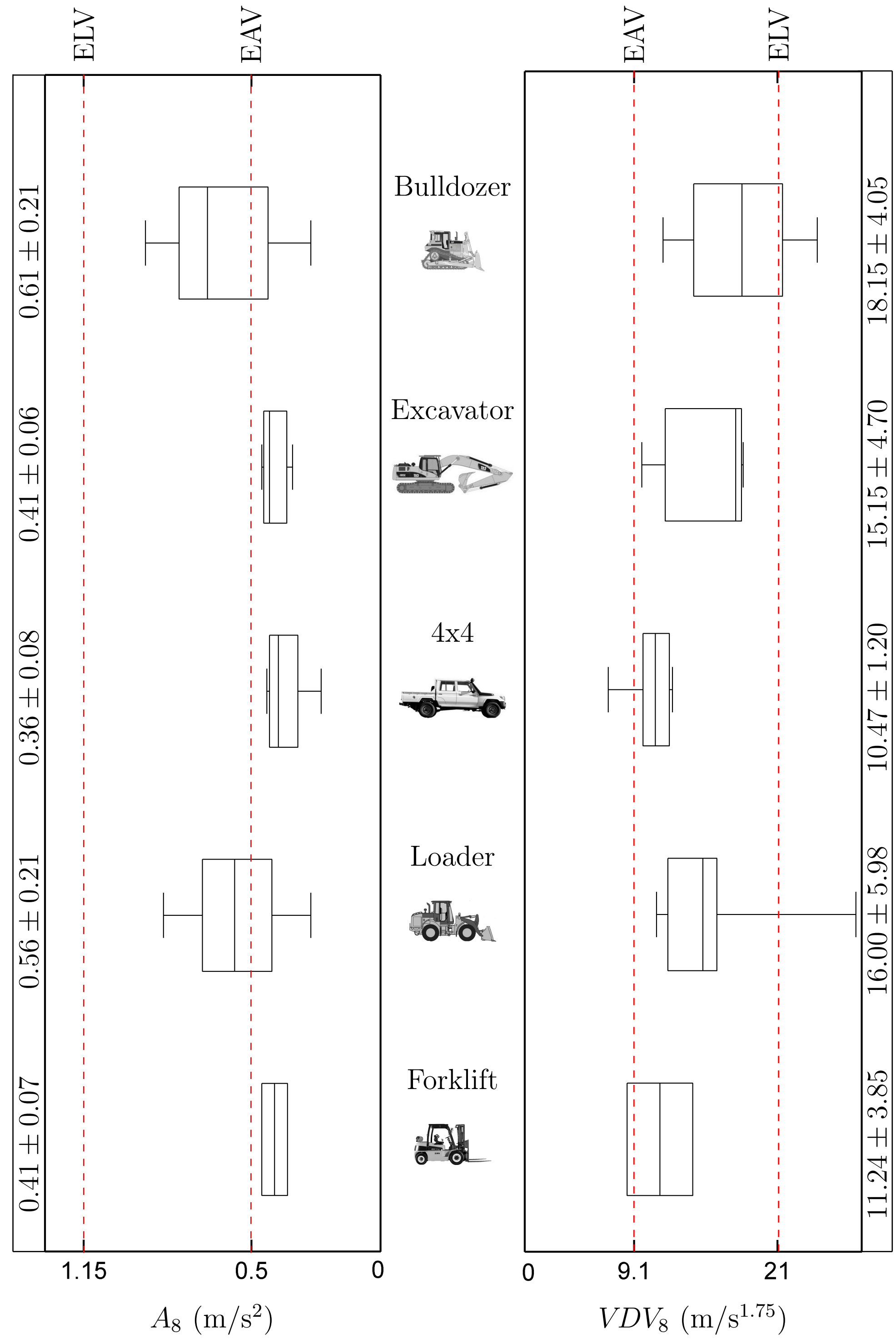
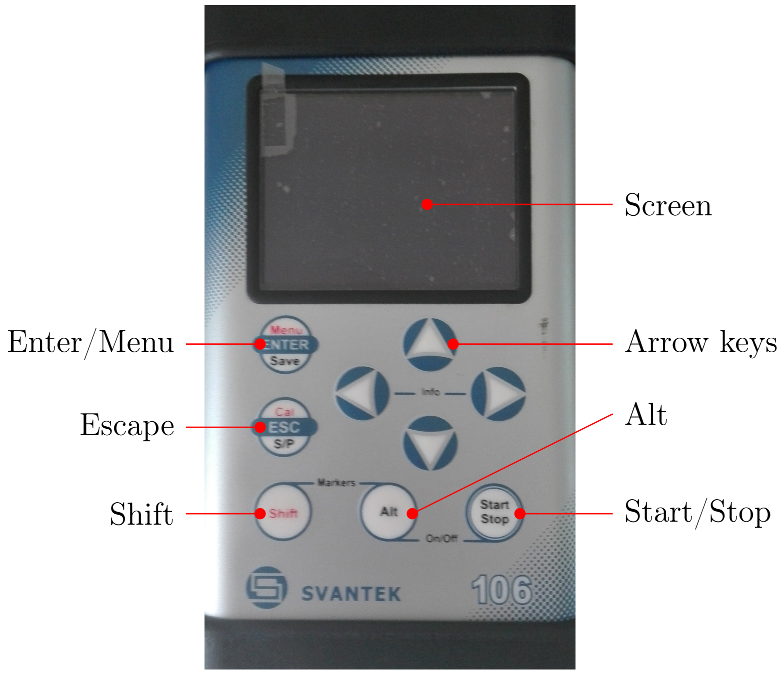


Figure 6.1: WBV of vehicle types

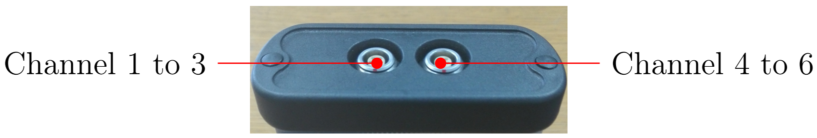
Appendices

Appendix A

A1 Svantek SV 106 human vibration meter



(a) Front view



(b) Top view

Figure A.1: Svantek SV 106 six-channel human vibration meter

A2 Informed consent form

UNIVERSITEIT•STELLENBOSCH•UNIVERSITY
jou kennisvennoot • your knowledge partner

STELLENBOSCH UNIVERSITY
CONSENT TO PARTICIPATE IN RESEARCH

Whole body vibration analysis for health on heavy mobile equipment

You are asked to participate in a research study conducted by Etienne Purcell (BEng), from the Department of Mechanical and Mechatronic Engineering at Stellenbosch University. The results will be included as parts of a thesis and research papers. You were selected as a possible participant in this study because you experience whole body vibration in a vehicle as part of your daily work.

1. PURPOSE OF THE STUDY

To determine the validity of a low cost whole body vibration measurement system and to determine the correlation between whole body vibration and back injuries.

2. PROCEDURES

If you volunteer to participate in this study, we would ask you to do the following things:

Allow the project to access the database entries of your medical history and physical data. You will also have to conduct your regular work with a measurement system attached to the vehicle that you are driving.

The research will stretch over a three month period at the end of 2016. You will only however to participate during the days that the measurement system is attached to your vehicle.

3. POTENTIAL RISKS AND DISCOMFORTS

The measurements will be done through a hard disc placed on the seat. This can cause mild discomfort during extended periods of testing. Further than that, no other discomfort or injuries can occur compared to a regular working day.

If you experience a painful lower back or any other injury that can influence your safety with which you can operate the vehicle, the tests will stop.

4. POTENTIAL BENEFITS TO SUBJECTS AND/OR TO SOCIETY

Through the successful completion of this project, you will have a lower risk of experiencing any whole body vibration injuries. This can contribute to lower medical bills and a higher income. The mining sector will also benefit from a healthier and more efficient workforce.

The research will also have benefits to society as a whole through a better understanding of how whole body vibration affects the lower back.

5. PAYMENT FOR PARTICIPATION

No payment or any other monetary benefit will be given to any participants.

6. CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. Confidentiality will be maintained by means of not copying any data and only using your information as part of the analysis of the research. No individual data will be published.

No information will be released to any third party for any reason. Video may also be taken from the inside of the vehicle. You have the right to view and access any video recordings. Only the research group will have access to any data and video recordings. The video recordings may however be used as part of scientific presentations. All videos will be erased after the completion of the research project.

7. PARTICIPATION AND WITHDRAWAL

You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. You may also refuse to answer any questions you don't want to answer and still remain in the study. The investigator may withdraw you from this research if circumstances arise which warrant doing so. If the researcher is unable to do measurements on the vehicle that you operate, your participation in the study will be terminated.

8. IDENTIFICATION OF INVESTIGATORS

If you have any questions or concerns about the research, please feel free to contact E Purcell at 0780881696 or 17067898@sun.ac.za or A Bekker at 0218084203 or annieb@sun.ac.za

9. RIGHTS OF RESEARCH SUBJECTS

You may withdraw your consent at any time and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research subject, contact Ms Maléne Fouché [mfouche@sun.ac.za; 021 808 4622] at the Division for Research Development.

SIGNATURE OF RESEARCH SUBJECT OR LEGAL REPRESENTATIVE

The information above was described to me by E Purcell in English and I am in command of this language or it was satisfactorily translated to me. I was given the opportunity to ask questions and these questions were answered to my satisfaction.

I hereby consent voluntarily to participate in this study. I have been given a copy of this form.

____

Name of Subject/Participant

____ ______________

Signature of Subject/Participant **Date**

SIGNATURE OF INVESTIGATOR

I declare that I explained the information given in this document to __________________ [*name of the subject/participant]* and/or [his/her] representative ____________________ [*name of the representative]. [H*e/she] was encouraged and given ample time to ask me any questions. This conversation was conducted in [*Afrikaans/*English/*Xhosa/*Other*] and [*no translator was used/this conversation was translated into* ___________ by _______________________]*.*

____ ______________

Signature of Investigator **Date**

A3 Measurement field sheet

Measurement

Vehicle number:			
Driver:			
Task:			
Location:			
Date:			
Start time:			
End time:			
Duration:			
Road condition:			
Visual shocks:	YES	NO	
Correct seat angle:	YES	NO	
	X	Y	Z
Reported WRMS:			
Reported VDV:			
Reported crest factor:			

Notes:

A4 Vehicle field sheet

Vehicle

Type:

Manufacturer:

Model:

Tyre type:

Seat condition:

Driver facing direction:

Armrests YES NO

Notes:

Appendix B

B1 Ratios to select applicable method

Table B.1: Ratios to distinguish between basic and additional methods

Measurement	CF	$^{MTVV}/_{a_w}$	$^{1.4VDV}/_{VDV_e}$
1	29.4	18.2	2.1
2	17.6	10.4	1.5
3	21.7	23.4	1.8
4	34.7	31.3	2.3
5	49.8	73.9	2.9
6	25.6	24.0	1.9
7	146.0	281.8	8.7
8	85.6	80.7	3.3
9	19.5	22.6	2.2
10	16.2	11.1	2.1
11	23.4	8.2	2.3
12	14.3	11.6	2.0
13	15.1	16.3	2.3
14	11.5	12.5	1.9
15	70.6	28.6	2.7
16	23.1	20.7	1.9
17	31.3	83.3	2.0
18	51.2	103.1	2.6
19	87.9	92.0	3.5
20	38.6	46.1	2.1
21	49.2	94.1	2.3
22	52.4	48.1	2.5
23	23.0	51.7	2.0
24	22.5	23.5	2.0
25	70.2	157.4	4.1
26	29.4	33.1	2.6
27	29.6	24.7	2.1
28	49.0	14.5	2.8
29	43.3	56.4	3.4
30	13.3	4.8	1.8
31	33.8	20.0	2.4
32	32.6	10.5	2.4

B2 Epoch size for normal data

Table B.2: Coefficient of variation on *VDV* for increasing epoch size

	CV (%)					
Measurement	1min	5min	10min	20min	30min	60min
1	37	22	16	9	6	-
2	22	6	4	2	1	-
3	25	10	7	5	3	1
4	32	14	10	6	0	-
5	55	38	31	24	18	13
6	31	17	12	7	3	0
8	57	48	45	40	31	2
9	53	30	20	10	8	-
10	31	7	4	-	-	-
15	50	40	33	22	13	7
16	30	16	12	7	4	3
17	44	32	26	20	17	12
18	63	49	43	36	26	12
19	42	29	21	12	10	0
20	33	21	16	11	8	4
21	40	29	25	21	20	15
22	42	28	19	11	6	3
23	50	33	25	19	16	10
24	31	17	12	9	7	4
25	37	27	22	12	7	0
26	32	15	10	6	2	-
27	37	20	11	5	3	1
28	54	15	12	1	-	-
29	78	45	3	2	-	-
30	39	28	16	1	-	-
31	32	14	7	3	2	-
32	30	11	6	-	-	-

Less than 25% Less than 12.5%

Table B.3: Coefficient of variation on RMS for increasing epoch size

	CV (%)					
Measurement	1min	5min	10min	20min	30min	60min
1	20	6	4	3	1	-
2	20	5	3	2	1	-
3	31	23	19	12	8	5
4	28	13	6	3	4	-
5	70	55	45	30	21	8
6	39	20	11	8	7	2
8	29	16	11	7	4	2
9	52	28	15	5	6	-
10	30	6	5	-	-	-
15	50	32	25	16	11	6
16	36	21	16	12	11	4
17	42	29	16	10	7	4
18	60	48	41	34	29	16
19	33	26	24	20	15	1
20	32	23	19	16	14	10
21	41	34	29	22	17	13
22	32	23	17	12	10	6
23	59	48	43	35	31	22
24	28	16	12	10	8	5
25	30	19	14	6	4	2
26	29	22	18	7	1	-
27	34	20	12	5	4	2
28	31	12	7	5	-	-
29	71	42	9	4	-	-
30	46	40	28	3	-	-
31	37	25	12	6	5	-
32	36	19	7	-	-	-

Less than 25%	Less than 12.5%

B3 Epoch size for non-normal data

Table B.4: Percentage of data 25% from mean *VDV* for increasing epoch size

	Data between limits (%)					
Measurement	1min	5min	10min	20min	30min	60min
1	61	83	97	99	99	-
2	70	100	100	100	100	-
3	78	99	100	100	100	100
4	81	94	100	100	100	-
5	33	51	53	59	88	100
6	64	85	100	100	100	100
8	75	54	33	24	26	100
9	32	52	79	100	100	-
10	52	100	100	-	-	-
15	55	38	40	55	97	100
16	72	87	98	100	100	100
17	66	71	92	93	92	100
18	51	50	45	22	46	100
19	57	68	76	91	100	100
20	63	78	81	97	100	100
21	64	67	65	80	78	99
22	71	72	79	99	100	100
23	31	56	69	86	91	100
24	64	91	90	100	100	100
25	61	69	78	100	100	100
26	52	83	100	100	100	-
27	59	75	100	100	100	100
28	19	87	100	100	-	-
29	15	18	100	100	-	-
30	29	52	93	100	-	-
31	60	94	100	100	100	-
32	62	100	100	-	-	-

More than 68%

Table B.5: Percentage of data 12.5% from mean VDV for increasing epoch size

Measurement	Data between limits (%)					
	1min	5min	10min	20min	30min	60min
1	38	49	46	81	98	-
2	41	96	100	100	100	-
3	49	81	96	99	100	100
4	60	68	81	100	100	-
5	16	24	31	31	35	51
6	34	53	53	92	99	100
8	46	11	14	0	17	100
9	13	8	31	74	100	-
10	29	98	100	-	-	-
15	24	18	8	45	67	96
16	41	54	63	97	98	100
17	41	25	33	63	83	79
18	27	23	12	9	38	66
19	31	47	39	68	74	100
20	35	45	66	75	92	100
21	41	37	31	42	34	42
22	48	44	29	71	93	100
23	16	28	32	38	47	76
24	34	58	77	79	87	100
25	28	37	29	44	99	100
26	31	63	73	100	100	-
27	33	46	67	99	100	100
28	11	58	77	100	-	-
29	6	1	100	100	-	-
30	9	16	36	100	-	-
31	25	57	93	100	100	-
32	36	67	100	-	-	-

More than 68%

Table B.6: Percentage of data 25% from mean RMS for increasing epoch size

	Data between limits (%)					
Measurement	1min	5min	10min	20min	30min	60min
1	80	100	100	100	100	-
2	84	100	100	100	100	-
3	69	82	89	90	100	100
4	76	94	99	100	100	-
5	33	52	60	77	87	100
6	48	74	98	100	100	100
8	70	94	98	100	100	100
9	31	61	91	100	100	-
10	51	100	100	-	-	-
15	49	68	73	90	100	100
16	54	76	92	100	100	100
17	61	67	91	95	100	100
18	37	49	56	49	47	81
19	45	58	65	86	94	100
20	57	70	81	92	100	100
21	37	42	53	72	87	91
22	63	80	88	94	100	100
23	22	24	34	34	43	63
24	68	87	99	100	100	100
25	64	85	94	100	100	100
26	66	73	94	100	100	-
27	64	85	92	100	100	100
28	63	93	100	100	-	-
29	13	22	98	100	-	-
30	22	15	38	100	-	-
31	43	65	100	100	100	-
32	55	81	100	-	-	-

More than 68%

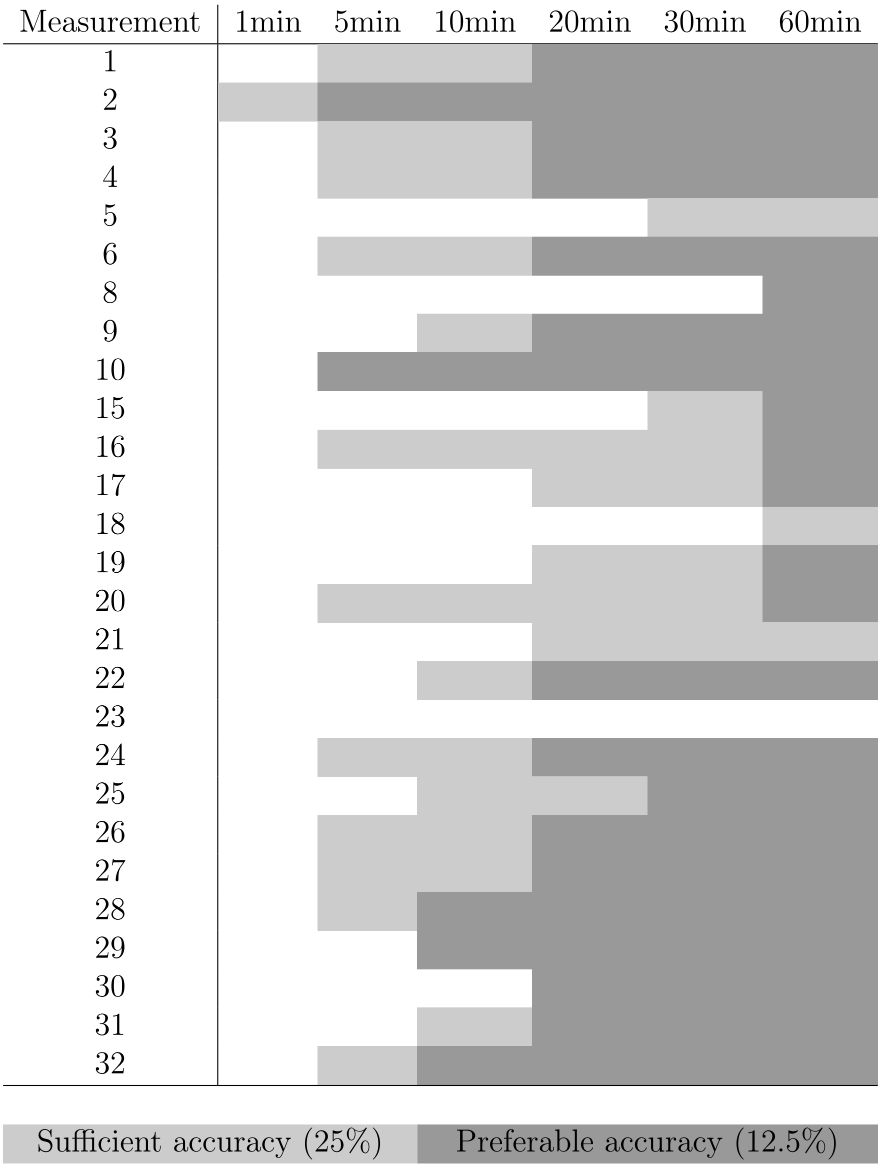
Table B.7: Percentage of data 12.5% from mean RMS for increasing epoch size

Measurement	Data between limits (%)					
	1min	5min	10min	20min	30min	60min
1	45	97	100	100	100	-
2	43	98	100	100	100	-
3	44	59	63	73	85	100
4	45	89	94	100	100	-
5	15	27	27	28	48	84
6	22	50	72	88	98	100
8	37	64	80	100	100	100
9	14	38	54	98	100	-
10	25	98	100	-	-	-
15	27	31	41	52	71	100
16	30	39	44	55	65	100
17	47	46	66	92	91	100
18	17	22	33	25	19	56
19	17	17	8	21	53	100
20	31	38	37	40	47	72
21	19	22	29	41	38	67
22	30	53	64	75	80	100
23	11	12	20	15	20	40
24	36	54	63	78	89	100
25	35	37	55	100	100	100
26	31	42	33	90	100	-
27	37	57	78	99	100	100
28	29	79	91	100	-	-
29	4	6	84	100	-	-
30	9	6	21	100	-	-
31	15	32	63	89	100	-
32	25	31	95	-	-	-

More than 68%

B4 Minimum achieved accuracy for all measurements

Figure B.1: Minimum achieved accuracy for each epoch size



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